PRODUCT DEVELOPMENT KNOWLEDGE MANAGEMENT PORTAL AND CASE STUDIES TO DEMONSTRATE THE NEED FOR BETTER DESIGN KNOWLEDGE MANAGEMENT USING IT

By

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ABSTRACT

Product development process is a complex one due to the involvement of highly coupled tasks and people over a certain period of time. So far there has been little success in capturing and storage of the knowledge that goes into making such a complex process in a easy to use and readily accessible way within a detailed framework.

This thesis presents a product knowledge management portal to categorize such vast knowledge effectively to achieve those objectives. It thus serves as a map and a knowledge repository of the entire product development process starting with the evaluation of customer needs, functional requirements and constraints subsequently leading to specific design parameters, the process variables and the final output of the product itself. Within this framework is also contained the details of each of these individual processes, lessons learned from the past experiences, task division and interactions between people and tasks over time and the interconnections and links between these processes themselves.

The thesis then studies three cases of products at two companies with different company cultures and size to learn how these companies manage the product development process knowledge using the above-developed framework. The results suggest the insufficiencies in different areas of knowledge backed by quantitative data. It also points out the common results and differences among the way companies manage the product development knowledge.

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MIT, Cambridge.

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Part I
Introduction and Background

Chapter 1
Introduction

"Knowledge is Power"
-Socrates, Philosopher

Any company that sells products or services and employs people who co-ordinate with each other in the process possesses knowledge. This knowledge could be in several forms including documents, software tools, standards, all of these or none at all (People in the company would 'just know' their jobs. That is to say that all the knowledge is in people's heads).

For instance, consider making a simple product like a disposable cup. It involves meeting the customer to know what his/her exact needs are, determining the dimensions of the cup that satisfy those needs, the knowledge of the process and equipment used to make the cup, actually manufacturing the cup, checking to make sure that the cup actually satisfies the needs of the customer and finally shipping the cup to the customer. The person (or people) involved in each of the processes mentioned above has to possess some knowledge about that process to deliver the necessary output in each stage. The entire process could be accomplished in a relatively short amount of time (say a few days). This knowledge may or may not be documented in some form or the other in the company in a formal way.

That was a simple example of a company producing one simple product. However most companies produce more than one complicated product across different product lines all of which may not be located under one roof. For example Boeing makes planes, which have 8 million parts, and takes 5-6 years to complete one such cycle described above. Consider Ford Motor Company. It makes 3-4 million cars each having about 2000 parts during final assembly (and each of them having about 25 parts on average) of several hundred varieties in several locations around the world with product development engineering teams with a combined strength of over a thousand people. Consequently the knowledge the company possesses about the processes is much more. In order for the company to perform efficiently, people have to have access to the knowledge about their work in a readily available and easily understandable form. They may gain that knowledge through their own experience or through other sources. Given the complexity of the process, it is easy to see how important the significance of each of these is. It is this that gives rise to a process to manage the knowledge itself.

1.1 Problem statement

We saw in the above paragraphs that complex interconnected processes in product development give rise to enormous amount of knowledge. Therefore, there have been many attempts to categorize knowledge in the academic and business worlds. The knowledge classification is inadequate due to several reasons.

The knowledge classification is too simple to derive any practical use out of it. For instance, classifying all knowledge into two simple categories as Explicit and Tacit serves only to differentiate two kinds of knowledge and lumps all available information as that which can be explicitly written down or well defined and those that are in the form of people's understanding that cannot be explicitly stated as the former. It doesn't help in providing a useful guide to the specifics of particular information that a user wants i.e., search ability of information is minimum. If knowledge were an ocean, it would be like separating it into water and aquatic life forms with no more differentiability of details. It wouldn't say anything about the types of aquatic forms – plant and animal, what types among these, etc.

Besides the inadequacies of the categories and the appropriate framework of classification, the knowledge itself that is classified is varied. There are very few frameworks that attempt to classify the product development process knowledge. Those that attempt to classify them are not detailed enough and miss important aspects of knowledge in the process. For example, though the Axiomatic Design approach does not attempt to classify knowledge specifically, it provides a basic framework. However this does not address certain knowledge types: knowledge associated with testing the product after manufacturing it, knowledge that people have gained through experience, etc. How do we differentiate that and make explicit in one classification?

There have been attempts to develop knowledge-based systems, which incorporate the knowledge classification concepts for easy information retrieval and browsing. However these are hard to implement and cost companies lot of time and money. Often they are narrow in their scope and are specific to a particular task or application. For example, a CAD system at most has a knowledge base that helps the user only in the design of the product. Similarly a CIM system helps in the manufacturing function. A Design Structure Matrix is a rich source of information about the interlinks among the tasks in a project. So each of them serves a narrow and specific function as far as the classification of knowledge goes.

So we see that there is no framework, which brings together all the product development process knowledge under its framework. Additionally, we also do not have a means to say how much of a company's knowledge is in the various sources (for instance, documents, groupware or people themselves) within the company and how exactly each source contributes to the company's knowledge base.

1.2 **Thesis objectives**

The objectives of this thesis are two fold.

Firstly, to come up with a framework that incorporates all the knowledge in the product development process. The framework should also clearly differentiate between tasks, people and time intensive information and has to serve as a repository of knowledge about the entire process and the accumulated learning about the process over time. This should be in a easy to understand, retrieve and browse form that promotes learning eventually leading to innovation.

Secondly, to use this framework to understand how companies presently manage knowledge. The thesis studies three cases (products) – Throttle body, MOCVD chuck, Electrostatic Chuck development processes. The cases studied are across two different type of companies one large – Ford with relatively longer product development cycle time; the other a smaller company, CVC with comparatively shorter product development cycle times and also a different work culture. The studies look into the various sources of knowledge related to these products – mainly documents, DSM, software and dependence on people as a means of knowledge transfer. It quantifies using the framework developed as to what kind of product development process knowledge is actually well documented and what information is under-documented; what sources are better for what kind of knowledge.

1.3 Overview of the thesis

The thesis is organized into four major parts.

Part 1, Introduction and Literature Survey

Chapter 1 gives a introduction to the subject of the thesis, the problem definition and talks about the need for the thesis.

Chapter 2 discusses the definition of Knowledge and the various classification frameworks that exist in the academic and business worlds to categorize knowledge. It also discusses their drawbacks and the need for a better categorization framework.

Part 2, The PDKM portal and methodology

Chapter 3 explains how the insufficiencies of the existing framework can be overcome and proposes a Knowledge Classification Framework (KCF) that is applicable to any product development process in general. It explains how this serves as a good knowledge repository and learning tool and explains how it should be used in different companies.

Chapter 4 begins with explaining the research methodology used to study the cases, the reasons for choosing the cases, the differences and similarities among them. It also points out about the drawbacks of the case studies.

Part 3, The Cases

Chapter 5 discusses the case at Ford namely, Case I with the throttle bodies of Ford automobiles. It quantifies the knowledge documented in the process based on the proposed KCF in the form of documents, DSM, software tools and tacit knowledge with the people.

Chapter 6 discusses the two case studies at CVC viz., the Case II with MOCVD chuck of CVC and then Case III with Electrostatic chuck. It quantifies the knowledge documented in the process based on the proposed KCF in the form of documents, DSM, software tools and tacit knowledge with the people.

Part 4, Conclusions and future work

Chapter 7 discusses the common results and differences among the different cases studied and draws inferences from all the case studies combined.

Chapter 8 takes a big picture view of the thesis and suggests further directions of research.

At the end are listed the references used and the relevant appendices to the thesis.

1.4 **Chapter summary**

Companies generally produce many products each of which requires knowledge and understanding of the processes involved. This knowledge is often large and is in several forms – documents, software tools, people's understandings from earlier experiences, etc. The challenge is to classify all the knowledge under one framework because such a framework for the product development process that includes the several aspects of the above knowledge sources does not exist. This inadequacy is further shown in the literature survey in the next chapter. This problem statement is clarified and the thesis objectives are outlined. The objectives are to come up with a framework to capture knowledge in the product development process and understand how well companies manage knowledge using this framework. The chapter also gives an overview of the entire thesis.

Chapter 2
Knowledge Management in Literature

"Little knowledge is a dangerous thing"
- Samuel Butler

Knowledge varies widely in both its content and appearance. It may be specific, general, exact, fuzzy, procedural, declarative, etc. The contents that form knowledge are of several types. It could in the form of data, best practices determined based on past experiences. The same knowledge can be conveyed in various forms – picture, prose, tables, etc. It could be in an easy to visualize or easy to understand form or otherwise. Its appearance and content could be different to suit the needs of different groups of people in the company. Before proceeding to understanding the challenges to having an efficient knowledge management process in place and the rewards it brings forth, it is important to know the meaning of the term knowledge management itself and to understand what it means in the context of this thesis.

2.1 Definition of Knowledge Management

The traditional paradigm of information systems is based on seeking a consensual interpretation of information based on socially dictated norms or the mandate of company bosses. This has resulted in the confusion between *knowledge* and *information.* Knowledge and information, however, are distinct entities. While information generated by computer systems is not a very rich carrier of human interpretation for potential action, knowledge resides in the user's subjective context of action based on that information. Hence, it may not be incorrect to suggest that knowledge resides in the user and not in the collection of information, a point made two decades ago by West Churchman, the leading information systems philosopher[1].

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[1] http://www.isss.org/lumCWC.htm

Concepts are best defined from how people use them. So lets try to define Knowledge Management (KM) by looking at what people in this field are doing. Both among KM-vendors (researchers and consultants) and KM-users there seem to be two tracks of activities and two levels.

The Two Tracks:

IT- Track: KM = Management of Information

Researchers and practitioners in this field tend to have their education in computer and/or information science. They are involved in construction of information management systems, AI, reengineering, group ware etc. To them, **Knowledge = Objects** that can be identified and handled in information systems. This track is new and is growing very fast at the moment, assisted by new developments in IT.

People-Track: KM = Management of People

Researchers and practitioners in this field tend to have their education in philosophy, psychology, sociology or business/management. They are primarily involved in assessing, changing and improving human individual skills and/or behavior. To them, **Knowledge = Processes**, a complex set of dynamic skills, know-how etc, that is constantly changing. They are traditionally involved in learning and in managing these competencies individually - like psychologists - or on an organizational level - like philosophers, sociologists or organizational theorists. This track is very old and is not growing so fast.

The Two Levels:

Level 1: Individual Perspective

The focus in research and practice is on the individual.

Level 2: Organizational Perspective.

The focus in research and practice is on the organization.

A 2x2 grid might look like this:

Track/Level	**IT-Track** **Knowledge = Object**	**People-Track** **Knowledge = Process**
Organizational Level	Re-engineers	Organization Theorists
Individual Level	AI-Specialists	Psychologists

Table 2.1a Knowledge track and levels

Even if this grid is to oversimplify things, it captures one essential issue: There are paradigmatic differences in our understanding of what knowledge is. The researchers and practitioners in the "Knowledge = Object" column tend to rely on concepts from Information Theory in their understanding of Knowledge. In fact, some researchers call this kind of knowledge as 'information' and not as knowledge itself.

The researchers and practitioners in the column "Knowledge = Process" tend to take their concepts from philosophy or psychology or sociology. Because of their different origins, the two tracks use different languages in their dialogues and thus tend to confuse each other when they meet.

2.2 Previous attempts at classifying knowledge

Classification of knowledge is perhaps as old as humans themselves. The early man must have classified edible things from those that were non-edible. People later must have classified all that is good from the bad. All that was probably lacking in structure. Aristotle is one of the earliest philosophers and thinkers to have come up with a more formal way of classification of living beings into plants and animals, each of them further into several categories giving rise to a more formal, taxonomy. The Romans had a hierarchical decomposition of commands and controls among their soldiers and generals.

The literature survey yielded many different types of classifications used by researchers in the academic world and the business world. The latter tends to be more specific to a particular business application while the former tends to be more general. Some of them are related to the product development process directly and some are not. Discussing all these types of classifications give us a fuller picture and enables us to understand each of their drawbacks, which we could later overcome through a new classification framework. Sections 2.2.1 to 2.2.11 lists these different classification methods.

2.2.1: A Use Model Knowledge categorization

Use Model		
Type of Task	Method	Tools
Know **what** facts	Database Search, Query, Match	PIM, CAD/CAM, CIM, Intranet, etc.
Know **how** procedures	Search, Match, Query, Create a new one	Intranet, Online Design Guides, Text, Video, Audio, People
Know **who** relationships	Remember relations, decide which are important, Search process models, Search project plans, ask experts	Process modeling software, project plans, People
Know **why** "Deep knowledge"	None available	People

Table 2.2.1a Use model knowledge categorization

Most design projects, for example as hood design or engine design require very specialized product and process knowledge. There is however a common thread among all of them. The above table by Whitney[2] shows it terms of the nature of task and knowledge. A typical design process has some or all of these characteristics. The first item in the table is well supported by current IT tools. However, relationship knowledge for completing a design task is something that is mostly with people and which they learn over time. For in-experienced engineers the lack of this information also limits their ability to use the procedures since they need to know the relationships in order to know what procedures to use. However, most formal design processes are too high level and do not adequately reflect the rich information exchange that typifies complex system design. A study of throttle body design at a large automotive company by Whitney is a good example.

2.2.2 Data, Info, Analytics, Knowledge, Wisdom

The following is a classification method designed for a data management in companies and has the flavors of the knowledge classification[3]. All knowledge can be classified into five groups – Data, Info, Analytics, Knowledge, Wisdom

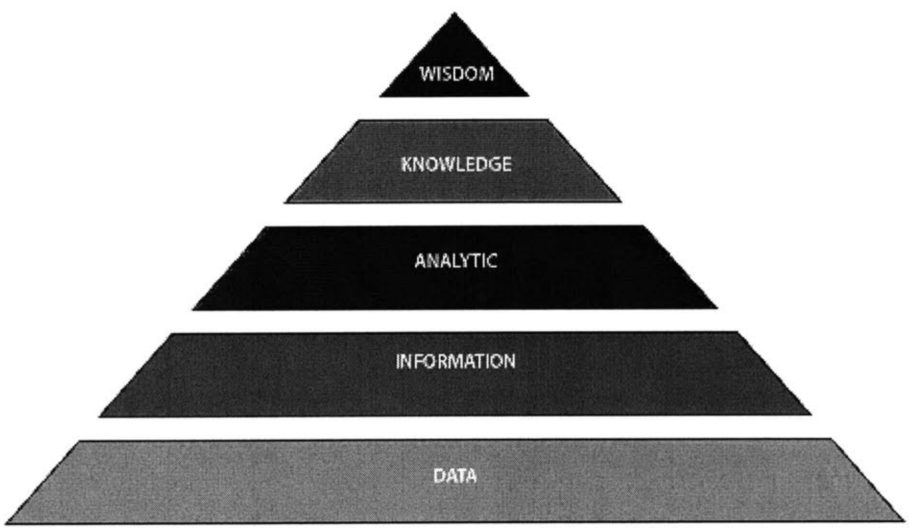

Figure 2.2.2a Classification of the various levels of understanding with the corresponding technology.

[2] Samir Patil and Dr. Whitney, MIT thesis

[3] Business Intelligence: Transition of data into wisdom, Data Management Review, November 2000

Data

Since the invention of the database management system and advances in data storage technology, organizations have been collecting, processing, storing and accumulating vast amounts of data about people, locations, transactions, concepts and events that can be easily analyzed. A great deal of this data is associated with the functional processes of the organization. For example, a grocery store collects data about the items an individual purchases at the time of checkout. The grocery clerk scans the products into the system, and the system identifies the price of the item and calculates the total sales price. Through this transaction, the system has collected the following data elements: item, quantity, price, date, which cash register, the grocery clerk and, in certain cases, who conducted the purchase if a club card was used. The following table is a representation of a transaction with sample data.

Item	**Quantity**	**Price**	**Date**	**Register #**	**Employee ID**	**Club Card ID**
Diapers	1	4.99	11/1/00	001	213	1209

Table 2.2.2a A Sample Data Transaction

Transaction processing systems are capable of collecting and processing voluminous amounts of data, which is the foundation for higher understanding.

Information

As the number of transactions that are processed and collected by the grocery store system increases, a wealth of data is collected. While each data element is a component of a transaction, what meaning can each data element provide? On an individual basis, data elements such as "item" do not provide meaning unless they are presented in conjunction with other data elements. The accumulation of data into a meaningful context provides information. IT applications that have ad hoc query and reporting capabilities provide users with the ability to extract data from a database and turn the data into information. For example, the accumulation of item, quantity and price provides information about the items that are purchased, the quantity and the price. By calculating the extended sales amount for each item, one can then rank and determine the item that generated the greatest and least sales by dollar amount. The following table is a representation of the accumulation of data into information.

Item	**Quantity**	**Price**	**Sales Amount**
Beer	265	6.85	1,815.25
Cereal	430	3.90	1,677.00
Bread	850	1.59	1,351.50
Milk	1100	1.20	1,320.00
Diapers	200	4.99	998.00

Table 2.2.2b The Accumulation of Data into Information

By taking data and placing it in a context that produces meaning, IT applications that have ad hoc query and reporting capabilities provide users with the ability to rise up from the data layer and create information.

Analytic

While combining data and meaning to create information is extremely useful, separating or regrouping information extends the value of information. Applications that have online analytical processing (OLAP) capabilities provide users with the ability to analyze information and determine relationships, patterns, trends and exceptions. The data that was collected by the grocery store transaction system and the information drawn from the data can be further analyzed by separating the information by period. The following table is a representation of separating information to create analytics.

Item	Period 1	Period 2	Period 3	Period 4	Total Quantity	Price	Sales Amount
Beer	35	75	100	55	265	6.85	1,815.25
Cereal	110	110	100	110	430	3.90	1,677.00
Bread	200	215	235	200	850	1.59	1,351.50
Milk	200	300	300	300	1100	1.20	1,320.00
Diapers	10	20	50	120	200	4.99	998.00

Table 2.2.2c Separating Information to Create Analytics

From the table that lists item quantities purchased by period, we can conclude that diapers and beer purchases at the grocery store are influenced by the period while cereal, bread and milk purchases are consistent throughout all four periods. Our findings were developed after we performed further analytics on the information drawn from the grocery store data. By performing analytics that entail separating or regrouping information, relationships, patterns, trends and exceptions can be identified to provide further understanding about the subject matter.

Knowledge

The next level of elevated understanding is knowledge. Knowledge is different from data, information or analytics in that it can be created from any one of those layers, or it can be created from existing knowledge using logical inferences. IT applications that have data mining capabilities provide users with the ability to identify hidden trends and unusual patterns within the data. These IT applications utilize various data mining techniques, which are based on statistics and algorithms to provide users with the ability to discover knowledge within their data. Deploying a data mining technique called rule induction against the grocery store data, it generated that *people who buy diapers also buy beer 50 percent of the time*. Without the use of a data mining application, identifying hidden trends or unusual patterns within the data would be extremely time-consuming.

Wisdom

Wisdom is the utilization of accumulated knowledge. As we discovered within the data, an unusual purchasing pattern was identified. From this knowledge, one can examine the analytical data set in the following table to develop a series of action items.

Item	Period 1	Period 2	Period 3	Period 4	Total Quantity
Beer	35	75	100	55	265
Diapers	10	20	50	120	200
Correlated Purchases of Beer	5	15	25	55	100

Table 2.2.2d Identifying a Purchasing Pattern

In periods 1, 2 and 3, additional sales of beer occurred above the rule that people who buy diapers also buy beer 50 percent of the time. However, in period 4, there were no additional sales of beer above the rule. By utilizing the newly discovered knowledge, we can analyze the beer marketing campaigns in period 4 compared to period 3 to determine effectiveness or change in strategy with the goal of increasing beer sales in period 4. We would also want to review period 2 purchases of diapers and beer to understand what events contributed to additional sales of beer above the induced rule. By utilizing knowledge, a higher level of understanding of the data is created.

Organizations that have been collecting data from their transactional systems have the opportunity to realize potential of the data as an asset to the organization and leverage that asset in a manner that provides greater understanding of the subject matter. The following table is a classification of the various levels of understanding with the corresponding technology.

Level of Understanding	Technology
Data	Online transaction processing (OLTP) systems

Information	Ad hoc query and reporting applications
Analytic	Online analytical processing (OLAP) applications
Knowledge	Data mining applications
Wisdom	The human mind

Table 2.2.2e Classification of Various Levels of Understanding with Corresponding Technology

While artificial intelligence attempts to emulate the human thought process, no technology has been able to replace the human mind. Most organizations have transitioned from data to analytics. Only those organizations that understand the value of data and technology advance to knowledge and wisdom, which in turn leads to the competitive advantages they could reap.

2.2.3 Axiomatic Design Framework

Though Axiomatic design literature[4] does not specifically classify knowledge, it provides a structure that we could build on for a new classification method. It is different from the one in the previous section, 2.2.2 because of the fact that it is specific to product design and development process while the latter is more general.

According to axiomatic design literature, the design world has four domains: the customer needs (CN) domain, the functional requirements and constraints (FR) domain, FR, the physical design parameters (DP) domain and the process domain(PV).

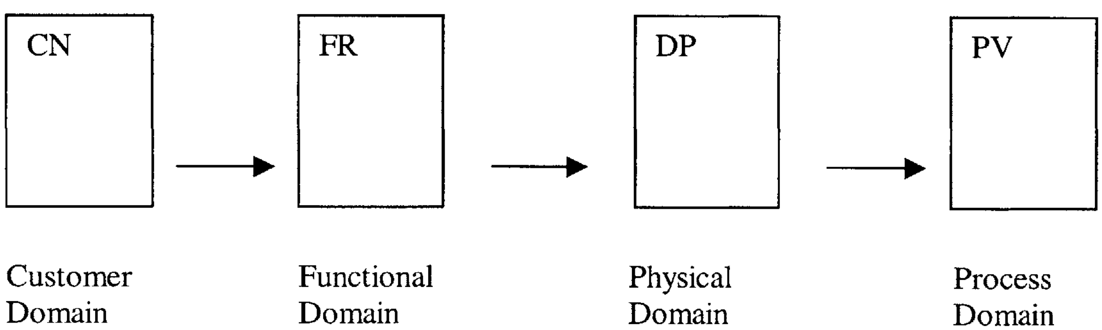

Figure 2.2.3 Axiomatic Design Framework

[4] Axiomatic Design, Nam P. Suh

The domain on the left relative to the domain on the right represents, "what we want to achieve", whereas the domain on the right represents the design solution, "how we propose to satisfy the requirements specified in the left domain."

The CA is characterized by the needs of that the customer is looking for in a product or process of systems or materials. In the FR, the customer needs are specified in terms of functional requirements and constraints. In order to satisfy the specified FRs, we conceive design parameters in the physical domain. Finally, to produce the product specified in terms of DPs, we develop a process that is characterized by process variables, PV in the process domain.

2.2.4 Explicit/Tacit

Depending on whether the knowledge could be stated in explicitly in the form of rules or data or the knowledge, which people possess because of their understanding and experience and cannot be laid out explicitly, knowledge is categorized into Explicit and Tacit knowledge[5]. The latter is the 'deep knowledge' as mentioned in section 2.2.1 or the 'Wisdom' in section 2.2.2.

However since this is a broad classification of a huge amount of knowledge, it is insufficient.

2.2.5 Local/Non-Local

Based on applicability knowledge can be classified as local and non-local[6]. The following table shows the differences between the two.

Local	**Non-Local**
Applies only to a limited set of conditions	Widely applicable across the business
Dependent on physical and/or geographic situation	Crosses process, industry, technical and cultural bounds
"Detailed" knowledge	"General" knowledge

Table 2.2.5a Local and Non-local knowledge

[5] Wisdom of the CEO, edited by Pricewaterhouse Coopers

[6] "Choosing your spots for knowledge management: A blue print for change", Peter Novins and Richard Armstrong; Cap Gemini Ernst and Young's Perspectives on business innovation journal, issue 1

Dr. Whitney has another has another way of looking at the differences between local and non-local knowledge. Local knowledge could mean the knowledge that is specific to a person whereas non-local knowledge is that which is derived from collective understanding. For example, say the marketing person knows that the customer wants a wallet that fits into the size of a standard back pocket. The person in the manufacturing department has a die that cuts leather blocks of a size within a certain range of length and breadth. These individually are local knowledge. When these two people meet to discuss the making of the wallet, they conclude that they can make wallets of a certain length and breadths that meet both their criteria and neither of them knew before. This latter knowledge was non-existent till the two people met. It the author's general observation from his case studies that the local knowledge generally tends to be documented better than the non-local knowledge.

2.2.6 Existent/Non-existent or Independent/Dependent

This is a classification by the author himself deriving from the earlier sections. Consider the earlier example, the marketing person knows that the customer wants a wallet that fits into the size of a standard back pocket. The person in the manufacturing department has a die that cuts leather blocks of a size within a certain range of length and breadth. These individually are existent knowledge. When these two people meet to discuss the making of the wallet, they conclude that they can make wallets of a certain new length and breadth range that satisfies both their criteria. This latter knowledge did not exist until the two people met. All non-existent knowledge is tacit by default. It is such knowledge that is often not found in documents and people often spend re-inventing the wheel in discovering non-existent knowledge.

2.2.7 Programmable/Unique

Based on transferability, knowledge is classified as programmable and unique[7]. The following table lists the differences among them.

[7] "Choosing your spots for knowledge management: A blue print for change", Peter Novins and Richard Armstrong; Cap Gemini Ernst and Young's Perspectives on business innovation journal, issue 1

Programmable	Unique
Rule-based knowledge. E.g.: If condition x is present, then the best approach is y.	Judgment-based
Can be applied multiple times without losing validity	Context sensitive and applied to specific situation
"Learning from history" to avoid repeating mistakes	Projecting into possible future problems
High transferability	Lower transferability
Easy to automate	Difficult to automate

Table 2.2.7a Programmable and Unique knowledge

2.2.8 The four knowledge classes

Based on both the applicability (section 2.2.5) and transferability (section 2.2.7), knowledge falls into four categories[8]. The following table illustrates that.

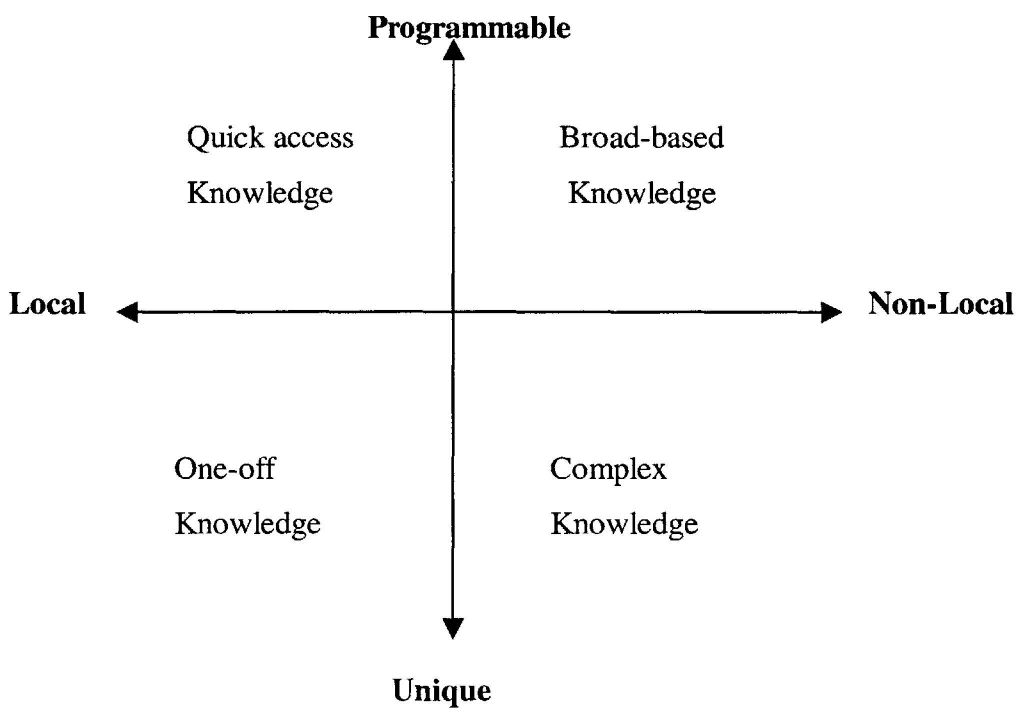

Figure 2.2.8a The four knowledge classes

[8] "Choosing your spots for knowledge management: A blue print for change", Peter Novins and Richard Armstrong; Cap Gemini Ernst and Young's Perspectives on business innovation journal, issue 1

Quick Access Knowledge

A piece of knowledge may be easily transferable (even programmable) but not very broadly applicable. For example, a reservations clerk in the Ritz-Carlton Hotel may learn that when Mr. Smith books a room, he wants a non-smoking one. This is a piece of knowledge easily transferred to others throughout the chain, but not very broadly applicable. (We cannot infer, for example, that all people from Smith's hometown are non-smokers.) The term "quick access" makes sense for this kind of knowledge because it is best managed by placing it in an accessible spot--most likely a sophisticated database--for use if and when needed. It would be a mistake to distribute this knowledge proactively to all personnel, just in case they might someday need it.

Broad-Based Knowledge

Other pieces of knowledge in the organization may be both easily transferable and broadly applicable. An example might be the organization's personnel policies, such as the knowledge of how to fill out a timesheet. With such "broad-based" knowledge types, it does make sense to broadcast to the organization by packaging the knowledge and distributing it proactively. Unfortunately, there is a tendency in firms to think more knowledge is broad-based than actually is; this is the source of the "information overload" felt by so many employees. One antidote is to broadcast information about how to access commonly needed knowledge, rather than broadcasting the knowledge itself.

Complex Knowledge

When a piece of knowledge is broadly applicable but not easily transferable, it is best transferred through structured training efforts. An example of such complex knowledge might be, in a consulting firm for example, the knowledge of how to manage a large-scale project. Many people in the organization need this knowledge, but the vicissitudes of good project management are largely resistant to hard-and-fast rules. In other industries, the approach to managing complex knowledge transfer is often apprenticeship. In both cases, there is recognition that the learner must develop a feel for the area that can only be gained through proximity or attention to someone already knowledgeable.

One-Off Knowledge

Finally, there is knowledge in organizations that is neither easy to transfer nor broadly applicable. A network manager in one office may know a great deal about configuring Macintosh systems, but if most of the organization uses Windows, the knowledge is not worth sharing broadly--and would be difficult to transfer in any case. Because the payoff of managing this category of knowledge is very low, it makes little sense to focus knowledge management efforts here. It is sufficient to support the establishment of informal, special-interest networks of people who might benefit from interacting occasionally with each other.

These brief notes already make it clear that thinking about knowledge in terms of applicability and transferability yields much clearer guidance for management than thinking of it in terms of domain. In all four cases, as in most areas of business, the best form of management is a careful balance of influencing people's behavior, introducing effective processes, and putting in place supporting technology. The mix differs, however, with the category. Quick Access knowledge, for example, is highly amenable to computerization, and management here should be at its most IT-intensive. Complex knowledge, on the other hand, demands the highest level of people management. The four categories have clear management implications, too, for levels of investment and effort. One-Off knowledge yields little return on high management effort. Complex knowledge management may represent the single greatest source of competitive advantage.

2.2.9 Levels of knowledge sharing Based on the levels of communication for knowledge sharing among individuals knowledge can be classified in the following way.[9]

[9] "Choosing your spots for knowledge management: A blue print for change", Peter Novins and Richard Armstrong; Cap Gemini Ernst and Young's Perspectives on business innovation journal, issue 1

Source/Beneficiary		Origin	
	Levels	One	Many
Recipient	One	Apprenticeship Coaching Mentoring	Networks
	Many	Presentations Books Articles	Leverage

Table 2.2.9a Levels of knowledge sharing

Individuals are most comfortable with knowledge sharing that originates with individuals. A single knower envisions himself imparting knowledge to one other person, or imparting knowledge to many other people. Similarly, when it comes to gaining new knowledge, he is apt to think of that knowledge being imparted to him by some one other person, who is addressing either him alone or him as part of a group. Table 2.2.9a shows that this mindset of one-to-one or one-to-many knowledge transfer is only half the universe of possibilities. It is usually the poorer half. The real opportunity lies in the realm where individuals and companies are least comfortable--knowledge transfer from many to many.

A company learns more in a day than an individual learns in a career. It makes sense, then, that when it comes time for an individual to make a business decision, he or she will do better to draw on the knowledge of the total organization rather than the knowledge of a specific individual, however intelligent. When a decision-maker floats an inquiry with a group of advisers, he is inviting knowledge transfer from many to one. When a project team raises questions on a networked discussion database, the transfer taking place is many-to-many. Both hold the promise of applying greater amounts of useful knowledge to people at the point in time when a decision needs to be made.

Knowledge transfer from many to many is generally comfortable and so engineers and managers still continue to tend toward their traditional means of acquiring knowledge individually and from trusted individuals. And as they begin to experiment with broader scopes, they will quickly run up against a disconcerting sense of loss of control. (Is too much knowledge being given away too broadly?) Nevertheless, the allure of many-to-many knowledge transfer is already undeniable; what else to account for the wild popularity of groupware--a technology that has yet to prove itself in many hard results. However, the recognition is growing that the real leverage to be gained from knowledge assets is in this kind of transfer, and that knowledge management efforts should focus here first.

2.2.10 Stages of knowledge

According to Roger Bohn[10], based on the changing nature of the knowledge and the process of learning there are eight different stages of knowledge. The following table shows them

Stage	Name	Comment	Typical form of knowledge
1	Complete ignorance		Nowhere
2	Awareness	Pure art	Tacit
3	Measure	Pre-technological	Written
4	Control of the mean	Scientific method feasible	Written and embodied in hardware
5	Process Capability	Local recipe	Hardware and operating manual
6	Process Characterization	Tradeoffs to reduce costs	Empirical equations (numerical)
7	Know why	Science	Scientific formulae and algorithms
8	Complete knowledge	Nirvana	

Table 2.2.10a Stages of knowledge

[10] Roger E. Bohn , "Measuring and managing technological knowledge", Sloan Management Review, Fall 1994

A Simple Example of Knowledge Progression over Time

Knowledge increases through learning. Much learning is simply increasing the precision and accuracy of parameter estimates within a single stage, but sometimes learning shifts the knowledge to the next stage. To illustrate, using familiar technology suppose you are baking cookies for the first time. You hope to make chocolate chip cookies, but have only a vague idea of a good recipe (raw materials) and procedure (control variables). You have a standard oven, which you were told to set at 350 degrees.(20)

The first step is to define your output measure, Y. It consists of a combination of taste, texture (hard or soft), and appearance.

Stage One -- Complete Ignorance. You don't even know what influences cookie characteristics, so when the results change, you consider it "random."

Stage Two -- Awareness. You rack your memory, observe others in the kitchen, and begin to build a list of possibly relevant input variables, including the list of ingredients, baking time, outdoor weather (rainy, cloudy, clear), time of day, amount and brand name of each ingredient, and a vaguely defined "mixing procedure."

Stage Three -- Learning to measure key variables. You use your watch to measure cooking time, measuring cups to measure raw materials, an outdoor thermometer and hygrometer for the weather, and a clock for the time of day. You have no detailed metric for mixing procedure, so you throw everything into one bowl and count strokes of the mixing spoon.

Stage Four -- Control of the mean. You get a countdown timer and develop a procedure to take the cookies out of the oven after a set amount of time. You can control outdoor weather only crudely, by baking on days when the weather is of a particular type. You decide not to bother controlling for time of day since it does not seem to make any difference. Control of the ingredients is straightforward, using a standard measuring cup; that is, for the raw materials, stage three leads immediately to stage four.

Stage Five -- Process capability and a recipe. You practice measuring ingredients until you can do it with 95 percent repeatability. You write down a set of instructions (recipe) that seems to produce "adequate" cookies. Your cookies now have a reasonably consistent taste, but texture and appearance are still variable and some cookies are burned.

Stage Six -- Process characterization. You run a series of experiments on many variables, including baking time, baking temperature, mixing time, and the exact amounts of flour, sugar, and liquid ingredients. You discover the effects of a 10 percent change in each of these variables on the cookie characteristics. If a friend asks for a better baked cookie, you can now achieve it by varying either the time or the temperature. You discover that some variables, including weather and time of day, have no deductible effect on the output.

Stage Seven -- Know why, including interactions among input variables. You go to the local university library and take out textbooks on baking, which give mathematical formulas for outcome variables such as sweetness and surface texture. You calibrate those models using data from your own baking process. You can now produce a "near perfect" chocolate chip cookie. If someone asks for a healthier cookie (less sugar), you can produce it, and you know how much to adjust the baking temperature. Similarly, if you are in a hurry, you know how to increase the temperature and decrease the baking time without burning the cookies.

Repeat for secondary variables. Although you now have stage five control (a recipe) for about ten variables and a stage seven understanding (know why) of five of them, there will always be a host of secondary variables in your knowledge tree that have smaller effects. And there is no guarantee that you will learn about the most important variables first. For example, you may not realize that cookie size is important (stage two) until you are well into stage five for other variables. You can subject these additional variables to the same progression through the stages of knowledge. Variables include the brand and characteristics of raw materials (butter versus margarine versus inexpensive margarine, types of flour), the importance of sifting dry ingredients together before mixing, type of baking tray (aluminum versus glass versus iron), and use of a scale instead of measuring cups for more accurate measurement of raw materials. For casual baking, you would never bother to learn about some of these variables, but if you wanted to reduce costs or improve consistency, you would have to delve much deeper into these secondary variables.

Stage Eight -- Complete knowledge. Since there is an infinitude of potential secondary variables, you can never have complete knowledge of the cookie-making process.(21) But for practical purposes, you can say that you have reached stage eight when you have a model that will predict output (cookie) characteristics to an accuracy of one-tenth of the tolerance band, for changes in inputs across a 2:1 range, and including all interactions.

Amateurs may stop when they have stage five knowledge about the primary variables that affect taste. They can then bake decent cookies and throwaway batches ruined by low knowledge about secondary variables. But professional bakeries must track down additional secondary variables, especially those that influence costs. Here is a description of the situation at one famous baking company:

The effects of these knowledge stages can be summarized in the following table. The ideal style for knowledge management for the process as a whole is an uncomfortable hybrid as indicated by the bi-directional arrows for several features.

Feature	Knowledge at stage		
	1 2	3 4 5	6 7 8
Nature of production	Expertise based	⟷	Procedure based
Role of workers	Everything	Problem solving	Learning and improving
Location of knowledge	Worker's head	Written and oral	In databases or in software
Nature of learning	Artistic	Natural experiments	Controlled experiments, simulations

Nature of problem solving	Trial and error	Scientific method	Table look-up
Method of training new workers	Apprenticeship, coaching	←——→	Classroom
Natural type of organization	Organic	Mechanistic	Learning oriented
Suitability for automation	None	←——→	High
Ease of transfer to another site	Low	←——→	High
Feasible product variety	High	Low	High
Quality control approach	Sorting	Statistical process control	Feed forward

Table 2.2.10b Effects of knowledge stages

2.2.11 Classification in KBE literature

In the Knowledge based engineering system literature[11], knowledge is classified as Domain Knowledge Base (DKB) and Task knowledge Base (TKB). DKB is needed to represent the engineering knowledge applied during the design process. TKB is used as the body of knowledge built up as a product in a design. Both the domain and task knowledge require formal representation schemes, so that knowledge used during design, manufacture, testing, maintenance etc can be captured and maintained. For example, a DKB rule might choose one configuration for a component within a piston if the cylinder is above a particular bore size or weight and another configuration if the cylinder is below that size or weight. A TKB rule might look up the existing database, or specify that

[9] Taleb-Bendiab, A. Oh, V. Sommerville, I. French, M. Knowledge representation for engineering design product improvement. [Conference Paper] Applications of Artificial Intelligence in Engineering. Publ by Computational Mechanics Publ, Southampton, Engl. p 807-824

the material used to construct a crankshaft, be the least expensive material with properties allowing it to meet input constraints.

2.2.12 Systems Engineering decomposition

As applicable to the space systems[12], the following categories of information can be differentiated.

Why: the requirements define the customers needs and why the mission is worth conducting.

Which: The trades' analysis compares different mission architectures and determines which architecture meets the requirements and therefore the customer needs.

What: The design describes what will actually be built and operated to conduct the mission.

How: The program plan describes the organizational structure, resource allocation, funding profile, and schedule. In essence, it describes how the mission will be deployed.

When: As part of the program plan, the schedule describes when different mission development and deployment stages will occur and how they depend upon each other.

Where: Also as part of the program plan, the hardware flow details where the following are located: component procurement sources, sub-system integration facilities, test and validation sequence as well as checkout and launch facilities.

2.3 Tools that exist to aid Knowledge Management for product development

Technological knowledge may be located in people's head, word of mouth or other informal mechanisms; in formal procedure sheets for operators, handbooks, other written documentation; or embodied in machinery, firmware and software[13]. In this section we explore the formal methods that aid the knowledge management process for product development.

[12] J. Warmkessel, MIT course faculty: 16.89 Space systems engineering

[13] Roger E. Bohn , "Measuring and managing technological knowledge", Sloan Management Review, Fall 1994

We are aware that there is a huge amount of knowledge associated with the product development process. As the author discovered through his cases studies, companies usually do not have all the knowledge in a form that is readily accessible by others. In fact, they are insufficient in having the knowledge itself.

This thesis deals with the management of knowledge specific to a product development processes. It could be extended to cover many different products but that is not the primary goal of the thesis. The tool that the author has developed, as we will discuss in the later chapters, is specific to a particular product and its development process. Let us examine the tools that exist to aid this. Then we will discuss how these individual tools are insufficient by themselves. We will summarize our learnings about the insufficiencies of these tools and predict what an ideal Product Development Knowledge Management (PDKM) tool should have.

2.3.1 Documents

There are several aids to manage knowledge a company has. Let us start with the traditional and the commonly used method. The author's friend and colleague, Qi Dong says that the medical devices company that she worked with over the summer has a room full of documents. Supposedly these documents contain all kinds of information ranging from interviews and test results with potential clients to development of drugs and government regulations to them.

Documentation by itself is an art. The documenter has to have an idea of not only the content but also how to put together the contents so that the content itself is easy to use and ready to find. This has to take into account the specific needs of the people who are to use the documents presently and in the future.

Some of the better ways of documenting have been to include pictures (" A picture is worth a thousand words" – Old Chinese proverb), diagrams and tables wherever necessary. Some of the documenting specific to the product development process are:

(i) Voice of customer tables

ID	Voice of the customer data	Use data				
		What	When	Where	Why	How
1	Male, 26 years old	Wallet feels smooth	I take it from the pocket	In my hand		
2	Female, 35 years old	I want contents visible	I need fast access	Banks, stores, gas stat-ions	In a hurry	

Table 2.3.1a Voice of customer table

The above table shows a voice of customer table that documents the needs of the customer from a survey. Hidden in this table is a classification that we combine with the axiomatic design framework after extending both into a new portal for product development knowledge management. The what, when, where, why and how classifications by themselves aim to differentiate the voice of the customer knowledge into several pieces of knowledge that essentially emerges from human understanding. It thus provides a means to transform a piece of explicit knowledge into tacit knowledge in an explainable form.

(ii) Field reports

During the post design process, engineers often do tests of various kinds and write reports about making changes in the design in documents called, 'field reports' because the results may not be satisfactory. This often results in design rework and increases the product development process cycle time, which costs the company more money. This is more so if the product is new because engineers are more likely to make mistakes in that case than in a case where they had prior experience with design a similar product.

However, Qi also laments that a wide array of documents are unused or underutilized. Why? People often don't know what is in these documents in the first place. They often find it easier to ask a colleague about something they are not familiar with rather than going through these huge racks of documents. They feel that the latter is like finding a pin in a haystack. They claim that it saves a lot of their time to talk to an experienced colleague. Often they don't realize that they are using up the time of the other person that they are interacting with. The author has a similar experience with the documents in the earlier lab that he used to work for at MIT. Most people in the lab had no clue as to what a lot of the documents in the lab were there for. We all felt that these documents could be even conveniently trashed because nobody seemed to be using them.

British Aerospace believes that more than 80 percent of employees waste, on average, 30 minutes each day trying to retrieve information. It believes that it was sitting on a gold mine of information. Unfortunately, the wealth of information sources available to its employees was hampering, not enhancing productivity.

We should also notice that in the type of documents stated above, though the document may be doing a good job at documenting a specific part of the product development process – for example, the voice of the customer tables at understanding the customer's needs; the field reports at improving the design after it is made, etc. The scope of the documentation is limited to that particular aspect of the product development process namely 'understanding the needs of the customer' and 'rework' during the process. It is analogous to looking at the trunk or the tail of an elephant without knowing what lies in between. Hence they are insufficient.

2.3.2 Software tools

CAD/CAM systems:

There are various software modules that help in knowledge sharing and knowledge exchange. Computer Aided Design, Computer Aided Manufacturing software, Project

Information Management all have an underlying database to aid the design, manufacturing and project management process. Purely geometric information created in CAD systems, as a part of the required information about design, is often inadequate since they don't easily take into account non-geometric information. It is difficult to represent objects that have no geometric components at all, like processes. The Design consultant softwares, which support these systems, are similar.

Intranets and company hard drives:

Company intranets are used as a knowledge repository, which people can use anytime to browse and retrieve information related to their work. At AT&T, most specific groups, such as R&D, customer products have their own websites. Each website has feedback capability and a mechanism for responding to suggestions and queries. There are chat rooms for exchanging ideas and posing problems, inter-conferencing for global virtual meetings over the internet and collaborative websites for projects, containing virtual file cabinets about the project and information about the team members. However, the big problem facing AT&T in regard to its KM effort is whether to allow employees to customize their desktops and use intelligent agents to pull down enormous volumes of data. Also, inside a large corporation, there may be dozens or even hundreds of intranets, each with hundreds of thousands of pages on it. And these intranets are controlled by very small, very fragmented groups of people. Therefore there is a need for an enterprise knowledge portal or a product knowledge portal—a single point of access to enterprise/product resources. According to Gerry Murray[14], director of KM research at IDC, the grass-roots intranet and Web page efforts are not coordinated. "They use different terminologies, taxonomies and standards. None of the Web sites are intended for external consumption. The control processes of content management and Web publishing are not normally placed on internal Web efforts. But that is starting to change." The new portal technologies are being used to create a desktop "cockpit" that gives each individual user everything they need to do the job in one place. "These portals don't have

[14] All quotes from Knowledge Management: Big challenges and big rewards, CIO special suppliment, Septemer 1999.

complete functionality, but they provide that single point of access into all the applications and collaborative tools," says Jennie Grimes, director of e-intelligence solutions in HP's Business Intelligence Unit. "They also include the taxonomy for finding the inference capabilities that are required to personalize information and push out information to users."

Jim Pflaging, president and CEO of Intraspect Software Inc., a provider of collaborative KM software based in Los Altos, CA recalls the recent occasion when he hired a new vice president, handed him the corporate business plan and told him to go into the corporate "group memory" on a central server and pull up the business plan folder. In it were all the documents, conversations and e-mails that had been generated in the process of creating that plan. "He came back and said he learned more about the company from that information than any business plan could ever teach," says Pflaging.

Besides these tools, "In a typical organization, 80 percent of the documents are sitting on individuals' hard drives" says Patricia Peper, Xerox Docushare marketing manager. "Unfortunately, these documents are largely inaccessible to others, so people spend a great deal of time reinventing the wheel".

Email:

Email is a popular way of substituting for people-people communication other than direct and telephone conversations. This form of knowledge capture lacks any structure since the email files can at best be organized into several folders. So they are more suitable as an informal means of learning similar to people-people communication methods.

DSM/DM:

Design Structure Matrices captures the links among the various tasks and the responsibilities of various people and teams involved in the process. Similarly, Functional Requirements/Design Parameters Matrices captures the knowledge related to how the design parameters were decided based on certain functional requirements and constraints well. We will study the specifics as to what forms of knowledge they capture well in the but all these are at best good at capturing few types of knowledge categories and see how they too are insufficient.

Knowledge based/Expert systems:

Knowledge based engineering is an engineering technology in which the knowledge about the product, e.g., the techniques used to design, analyze, manufacture and assemble a product, is stored in a comprehensive product model. The knowledge includes design rules, engineering standards or rules of thumb about attributes of the physical product such as geometry, material type or functional constraints as well as process information. Therefore, product information on fabrication and assembly processes, material availability and quality, service history, or other attributes relevant to a company's practices will be part of the product model.

The knowledge based/Expert systems promote concurrent engineering by providing a framework to incorporate design, engineering and manufacturing knowledge into a single product model that the company can use consistently through the product design phase. For instance, Concept modelers are examples of KBE systems, which incorporate several Artificial Intelligence techniques particularly in the area of knowledge acquisition and knowledge based system development. Similarly there are expert systems based on axiomatic design principles.

Though they serve a wide array of functions, these systems are generally cost intensive and take long time to implement. Besides, they have been proved to be insufficient when dealing with design problems that can be given an optimization formulation in the literature[15].

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[15] Johan Malmqvist, "Optimization in a design system for complex products", Advances in Design Automation – Volume 1, DE-Vol. 44-1, ASME 1992

"Most companies don't have good knowledge bases. KM will only be as good as the knowledge base you build," says John Stetak, vice president of marketing at Input Software Inc.. Therefore the need for a good product knowledge portal is higher.
Xerox feels that its knowledge-based systems have created problems, particularly in dealing with knowledge obsolescence. "The knowledge base is getting large enough to employ usage patterns to determine what content is most useful, and what isn't being used at all" says Dan Holtshouse, director of business strategy knowledge initiatives at Xerox. Some of the tips are not active anymore. So a process that keeps it updated is needed along with these systems.

Enterprise Software Solutions:

There are abundant knowledge tools that serve specific business functions. For example a supply chain management tool has databases to facilitate supply and delivery of incoming and outgoing goods at a company. A client relationship management tool would have a knowledge base to help clients better.

A third example could be workforce management systems. Another element of KM has to do entirely with the management of the workforce. Managing the workforce entails not only knowing about the time and resources that employees consume, but also the content of their work. It involves integrating structured data with less structured data—statements of work, contracts, engagement reports and status reports—all with the ultimate purpose of "helping employees make judgments," says John Lucas, president and CEO of Account4.com (a division of Work Management Solutions), in Newton, MA. Workforce management is also a means of understanding how people do their work and using that information to create tools that help new employees progress more rapidly. It can also serve as a solution to the problem of "expertise walking out the door" when employees leave a company, says Lucas.

However, most of these tools again are specific to a certain function as mentioned before.

Data Mining tools:

Like we saw before, knowledge is different from data because it comes from using logical inferences from the latter. IT applications that have data mining capabilities provide users with the ability to identify hidden trends and unusual patterns within the data. These IT applications utilize various data mining techniques, which are based on statistics and algorithms to provide users with the ability to discover knowledge within their data. Without the use of a data mining application, identifying hidden trends or unusual patterns within the data would be extremely time-consuming. Though these tools are good at generating rules of thumb, etc they miss out on several other types of knowledge.

Thus we see from sections 2.3.1 and 2.3.2 that a comprehensive documentation methodology of the entire product development process, which takes into account both the interactions of knowledge and people over time (please note the words carefully) is not found in the literature.

2.4 Summary of the classification methodologies

The following table shows the relation between the knowledge management definitions described in section 2.1 and the classification methods discussed in the section 2.2. The table serves to categorize what sub-divisions of the methods are IT friendly and what are more people-oriented. A more detailed discussion about comparing the thesis proposed product development knowledge management portal to these methods is presented in the following chapter after the discussion of the portal.

Classification method or tool	IT-Track Knowledge = Object	In betweens: Some knowledge = Object; Some knowledge = Process	People-Track Knowledge = Process
2.2.1 Use model knowledge categorization	Facts	Procedures, Relationships	Why
2.2.2 Data, Info, Analytics, Knowledge, Wisdom	Data, Info	Analytics	Knowledge, Wisdom
2.2.3 Axiomatic Design framework		Customer needs, Functional Requirements, Design parameters, Process variables	
2.2.4 Explict, Tacit	Explicit		Tacit
2.2.5 Local, Non-local	Local		Non-local
2.2.6 Independent, Dependent	Independent		Dependent
2.2.7 Programmable, Unique	Programmable		Unique
2.2.8 The four knowledge classes	Quick access knowledge	Broad-based knowledge, One-off knowledge	Complex knowledge
2.2.9 Levels of knowledge sharing	Many-many	One-many, many-one	One-one
2.2.10 Stages of knowledge	Measure, Control of mean, Process capability, Process characterization	Know why	Awareness, Complete knowledge
2.2.11 Classification in KBE literature	Domain knowledge base		Task knowledge base

Table 2.4a Knowledge categorization in the literature

2.5 Chapter Summary

This chapter described the meaning of knowledge management and the various kinds of categorization of knowledge in the academic and business literature. It also described the various tools that are available and serve as knowledge repositories. We discussed their limitations of the various categorization methods and the tools individually and paved way for the development of an ideal PDKM portal.

Part II
The PDKM portal and methodology

Chapter 3
The PDKM Portal

"There is no subject so old that something new cannot be said about it. "

Fyodor Mikhailovich Dostoyevsky

3.1 Introduction

We have seen from the literature survey that each of the different knowledge classifications and tools fail to capture certain aspects of the product development knowledge. The table in section 2.4 clearly demonstrates that. Therefore there is a need for a portal that captures the richness of both IT amenable 'information' and people or process oriented 'knowledge'. In the following section, we discuss what an ideal Product Development Knowledge Management Portal (PDKM portal) should have.

3.2 Features a PDKM portal should have

Brook Manville, director of knowledge management at the consulting firm McKinsey & Company in Boston, views the implementation of the general knowledge management portals to shift from the traditional emphasis on transaction processing, integrated logistics, and work flows to systems that support competencies for communication building, people networks, and on-the-job learning. Specific to the product development knowledge management portal that we are interested in the following would be some of the features that we have learnt that it should incorporate from the literature survey in the previous chapter.

Firstly, the knowledge the tool covers has to span the entire process. For example, it should contain knowledge about customer needs, design information, manufacturing or outsourcing, fulfilling the orders of the customer. It should also include knowledge from the past experiences, potential problems and ways around them, company policies and government regulations if any, glossaries of terms specific to the company, best practices codes, safety requirements, etc.

Secondly, this vast information should have connectivity between information and tasks. For instance, it should contain how one customer requirement eventually leads to a functional requirement and further to design parameter and so on till the product is finally made. Consider the wallet making company example again. In this case the PDKM portal should have links between the customer's voice that says, "The wallet should be easy to take out and put back into my pocket" and the functional requirements domain which says, "The wallet length and breadth should be 80% of a standard Jeans back pocket length and breadth" and further to the design requirements domain which says, "The wallet size should be 4 inch by 3 inch" and so on. Besides that it should also contain information about which teams were involved in gathering this data and making the decisions. It should also contain when these individual decisions were made. These kinds of information give immediate one-shot pictures of where the problems could be in the process. It also ensures trace ability of information and makes the process of learning on the job much easier.

Thirdly, this copious bunch of knowledge should be stored in a easily accessible form so that any particular information someone needs among this vast amount of knowledge is at their fingertips. This is to say, it should be easy to find a pin in a haystack if one wanted to. The easier this is, the better the source browsability is. So the portal should have a consistent and easy to work with framework that accomplishes this.

Fourthly, people should be able to access the information that they need as and when they want to. Priorities should be set on who accesses what information. This is to ensure appropriate security of the knowledge the tool contains and prevent some person from updating the portal with inaccurate information. After all, the learning of the company forms its right to intellectual property. The tool should have features that strive to maximize that. It should also enable easy updating of information in different segments of the portal for a sustained use by individuals using those segments.

In the following section, we describe such a PDKM portal. The author started with the framework of Qi Dong, which was included in her Ph.D proposal at MIT and refined the portal through periodic discussions with the author, as more categories of knowledge that needed to accounted for were discovered, during the course of the case studies.

3.3 The PDKM portal

Since we are interested in the entire product development process, we first divide the process into 5 major domains viz., the customer needs and enterprise strategy domain, CN, the functional requirements and constraints domain, FR, the design parameters domain, DP, the process domain, PV and the output domain, OP.

The following table shows what knowledge each of these domains contain.

Domain	**Knowledge contained**
Customer needs and Enterprise strategy, CN	All activities related to gathering of information about customer needs. In addition to that, the limitations that the management (for example on the cost and profitability of the product) or government policies (for example, on certain features of the product) impose on meeting those needs.
Functional requirements and constraints, FR	Knowledge related to evaluating the product performance requirements that are necessary and constraints that affect the functioning of the product as a whole, based on the customer needs.
Design parameters, DP	The specific design parameters of the product features that are decided so that the above functional requirements and constraints are met.

Process Variables, PV	Product manufacturing process specifications, performance and planning that enable to produce the output with the above DPs.
Output, OP	Knowledge about testing whether the product output so produced meets the CN domain needs or not. If it doesn't, then the knowledge about rework and updated information about the other domains.

Table 3.3a The PDKM portal framework

These five major domains are each sub-divided into 7 categories to include both the IT amenable and people oriented knowledge. The sub-divisions and what they represent in general are explained as follows.

1. WHAT

This includes knowledge that are facts or data about something. It is the lowest form of knowledge (similar to 'data' in section 2.2.2) and helps in understanding the basic functions and dimensions of parts, systems or sub-systems. Specifically, whats within the documents include:

(a) Definitions of any kind – parts, terms, etc

(b) Introductions to something in the documents

(c) Functions of parts, sub-systems, systems, etc

(d) Diagrams – conveying dimensions, schematics

(e) Category classifications – Class to which something is applicable, Method types, Design alternatives/types, Requirement types, Functional types, Prototype types

(f) Priorities – Requirement priorities

2. RULES

Rules are a higher form of knowledge requiring inferences from a given set of data or from past experiences and hence is more people oriented. They are knowledge about

(a) Past experiences - Do's and don'ts; corrective actions

(b) Empirical Formulae

(c) Safety rules

(d) Recommended practices, Best practices

(e) Rules of thumb

3. WHERE

Knowledge about where to find particular information. It is the author's observation that good documents generally contain references to other documents where one could find more information about something. This feature promotes learning better. So they include:

(a) Sources of information – about tests, procedures, etc

(b) References for more details

4. WHO

Who is the knowledge about

(a) Responsibilities of a person or team

(b) Ownership of a part or task

5. WHY

Knowledge that aims to explain why a certain thing is the way it is in the product or the development process.

(a) Why1 - The why that answers the question of requirements flow down. For example, the explanation for why a particular design parameter was chosen given a functional requirement belongs to this type of why. Another example could be why a particular functional requirement was set as it is, given a customer need or an enterprise strategy.

(b) Why2 – Often times towards the end of the product development cycle, there are problems integration problems though all the DPs were designed to fulfill the needs of the customer. The why that explains such unexpected system behavior (system integration problems) belongs to this type of why.

(c) Why3 - The why that explains why a particular design choice was made amongst the various options available. In other words, alternative designs: advantages and disadvantages. There are found within almost all the five domains.

6. HOW

Knowledge about implementation of a rule

(a) How1 – The solution to requirements, or the requirement flow-down. For example, how a functional requirement is fulfilled—the DP solutions.

(b) How2 - The interactions within each domain. For example, the interactions that are captured by the DSM belong to this category. The how knowledge may also concern the sensitivity of certain elements to the output and the dynamic relation of the elements to the total output.

7. WHEN

Knowledge about

(a) Timing/Sequencing of a particular task/s

These seven sub-divisions some are more IT amenable and some require understanding and experience of the people. The following table lists them under the two categories.

	IT-Track	**People-Track**
Sub-divisions	What Who Where When Some rules (E.g.: formulae)	Rules Why – Why1, Why2, Why3 How – How1, How2

Table 3.3a Subdivisions and the two tracks

A complete table comparing this portal with the other knowledge classifications and tools can be found in the following section.

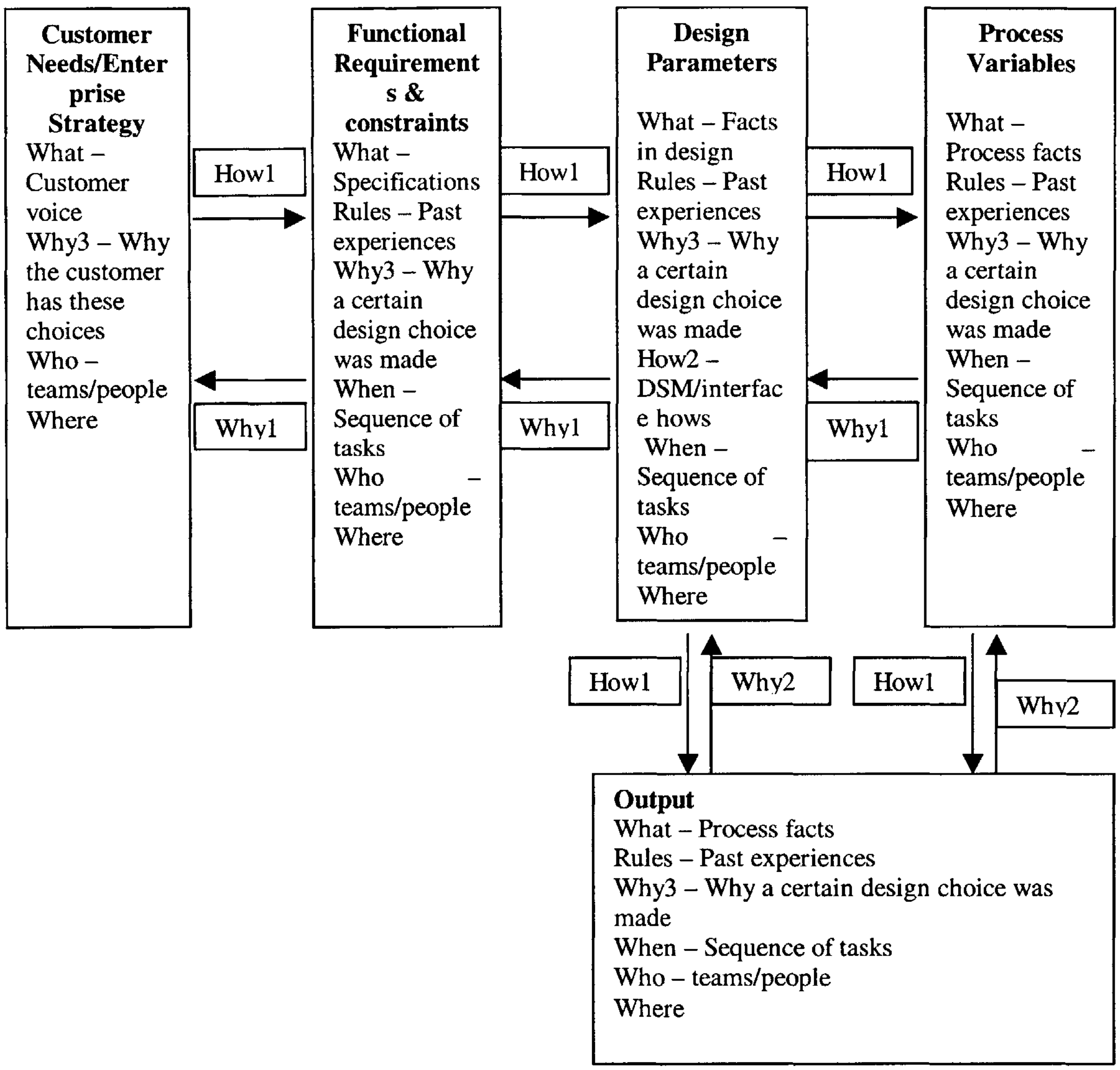


Figure 3.3a The PDKM Portal

A sample example of building the portal for the case of the wallet design is shown in the following figure.

Customer Needs and Enterprise strategy Domain

What – Customer says, 'Wallet should be easy to put in and take out of my pocket'

Rules – While selecting customers to survey its best to choose 50% of them who are male adults between 16-30 age group and the other 50% between 30-50 age group.

Where – To find information about the details for conducting the customer survey look into the 'customer survey' guide.

Who – Mr. A, Ms. C conducted the survey and know more about it. Mr. C knows about the company policy and government regulations for making the wallets.

Why – Why should you pick the population group as stated in the rules OR explaining that choosing the wrong group would result in making the wallet for a non-targeted market as shown by the previous generation wallet making process.

How – How to go about doing the customer survey. What are the tasks involved and how are they dependent on one another.

When – When the survey was done and the chronology of all the tasks involved in this domain

Functional Requirements and Constraints Domain

What – Wallet should be less than 80% the size of a Levis 33x34 jeans back pocket.

Rules – The wallet ratio of length and breadth should be in 3:2

Where – For more information about wallet requirements see 'What the customer means' guide.

Who – Mr. A and Ms. D are involved in evaluating what the customer means and converting the needs to functional requirements.

Why – The length to breadth ratio is 3:2 because the company has leather cutting dies which can be manipulated only in that ratio.

How – How do the various tasks involved in the process interact among one another. How much is one task dependent on the other.

When – The chronology of all the tasks involved in this domain

Design Parameters Domain

What – Wallet lengths and breadth are to be of two types. Type 1 will have a size of 3 inch by 2 inch; Type 2 will have a size of 3.15 inch by 2.1 inch
Rules – The 3.30 inch by 2.2 inch wallet shouldn't be made though it satisfies all the FRs; The color of the wallet should be black.
Where – Look into the 'Wallet design' guide for more info.
Who – Ms. D and Mr. E and Mr. F worked on determining the DPs.
Why – The 3.3 inch by 2.2 inch wallet has become out of fashion because our previous generation wallet of that size has had dwindling sales for many years; Wallet can be of two colors tan and black. We choose black because it costs less to make it because it doesn't need the extra polish the brown one requires.
How – How do the various tasks involved in the process interact among one another. How much is one task dependent on the other.
When - The chronology of all the tasks involved in this domain. Tasks could be carried out in series or parallel or both.

Process Variables Domain

What – The buffer size between the stations in the assembly line is 50.
Rules – Safety rules to be followed during production.
Where – For more info refer to the 'Wallet production process and control' guide.
Who – The function of the quality control engineer is to inspect if the stitching along the edges are intact.
Why – Why all the rules in this domain exist; Why some processes shouldn't be carried out.
How – How do the various tasks involved in the process interact among one another. How much is one task dependent on the other.
When - The chronology of all the tasks involved in this domain. Tasks could be carried out in series or parallel or both.

Output Domain

What – Testing routines
Rules – The leather of the wallets that don't meet the quality control requirements should be recovered and sold to the company buyleather.com
Where – For more information refer to the 'Is your wallet good enough?' guide
Who – Mr. G knows a lot of this domain knowledge
Why – Why all the rules in this domain exist; Why some processes shouldn't be carried out.
How – How do the various tasks involved in the process interact among one another. How much is one task dependent on the other.
When - The chronology of all the tasks involved in this domain.

Figure 3.3b. A part of the PDKM portal for the wallet development case.

3.4 How the portal is better than the earlier classifications

All the classification methods explained in chapter two except the Axiomatic design, the Use model and the Classification in the KBE literature are general classifications that are not specific to the product development process. They were not designed with this process in mind. For instance, method 2.2.2 is more relevant to a sales or marketing department. Because of this reason alone there is a need for the PDKM portal. The PDKM is a map of the entire product development process as shown in Figure 1 so it satisfies the first requirement of the ideal PDKM portal.

All the methods are too broad to incorporate and structure the vast amount of knowledge under a few categories. For instance, though the tacit/explicit method differentiates the people aspect of the knowledge from that which is not, it lumps all the information into two major blocks. The PDKM incorporates both the IT amenable knowledge and people oriented knowledge into multiple categories as shown in Table 3.2 across five different domains.

The classification methods also do not satisfy our aim that there should be interlinks among them or a common thread by which a particular task's origin and end result can be traced. In other words, they do not capture how the development of the product has progressed. The PDKM portal captures that through the how1, why1 and why2 interlinks within the domains throughout the product development process. Thus it satisfies our second ideal in section 3.2.

The classification methods discussed in chapter 2 do not make the knowledge easy to access. For instance, though the local/non-local classification differentiates between local and non-local knowledge it does not clearly state where exactly within these the knowledge resides. So the source of the knowledge would not be clear to someone who wants to access it. The who and where sub-divisions in the PDKM portal does this more efficiently and so fulfills our third ideal.

Since the information related to the product development process is large and there are many people involved in the process and even though each person documents information related to his or her work, finding a certain piece of knowledge is difficult because each person has his or her own style of documentation (in the form of notes which could be detailed or brief in which case it is for the reference of that person alone) and place for documentation (For example, hard-drive, in their memory in the form of experiences, etc). None of the above methods cater to this aspect of the product development process. On the other hand, the PDKM portal promotes documentation for the use of multiple users in the process through its structure. Though the author has not actually implemented the portal in a real product development scenario, it is an important feature of the portal to have databases with appropriate security settings so that the right people have access to the relevant information and the company also protects itself of intellectual rights infringements. This takes care of the fourth ideal of the desired portal.

Besides these, the methods also do not differentiate clearly between how much of the development was done right the first time and how much rework was done and how they were done. The why2 sub-division of our portal differentiates that aspect of the product development process clearly.

Because of these reasons, the PDKM portal is a good way of not only the classification of knowledge but also its easy of use and retrieval in the product development process. In the next chapter, we use the portal to study the way companies manage their product development process knowledge.

3.5 Chapter Summary

The chapter proposes the features an ideal product knowledge management portal should have and proposes one such portal. It compares this classification methodology to the ones found in the literature and shows how the portal overcomes them.

Chapter 4

The case study methodology

"Not everything that can be counted counts, and not everything that counts can be counted."

-Albert Einstein

The last chapter presented the PDKM portal. Now we move on to study how companies manage their product development process knowledge. We scan the knowledge sources used in the companies for this and classify the knowledge within them according to our portal.

4.1 Knowledge sources

The knowledge that is involved in this long process is very vast. As described in chapter 2, it is found principally in three sources viz.,

(a) Knowledge and understanding of the team members

(b) Documents of various forms (design guides, help manuals/folders, DSM etc), which assist team members in various stages of the process.

(c) Software tools and aids.

As applicable to most product development processes in companies, among these (a) and (b) are the primary forms of knowledge. However among these two, only (b) is somewhat quantifiable. Also, documentation on paper has been the primary method that most companies rely on for managing the product development process knowledge. These documents serve as the chief means of knowledge retention and propagation among the employees of the company – both among peers and those of successive generations. Before we fulfill the second objective of this thesis, which is to study the way companies manage their product development knowledge using the portal, we need to come up with a methodology to quantify information in these documents. This chapter describes the methodology we would be using for the same.

4.2 Knowledge measuring methodology

The documents have information principally in the form of

(a) Sentences,

(b) Diagrams,

(c) Tables or charts.

Each of these conveys something related to product design and development process and forms the knowledge that we are after to quantify and relate to the portal framework. So we would have to classify each of these pieces of knowledge into the right domain (CN, FR, DP, PV, OP) and the right sub-divisions (what, where, who, when, why1, why2, why3, how1, how2 and rules) among each of these domains.

After classifying a piece of knowledge into one of the above domains and sub-divisions, the number of lines of each piece of information was counted.

The unit of the knowledge was considered to be a line. To ensure consistency in counting the following procedure was adopted.

(a) Sentences were easy to count – For instance, two lines of text about function of a part as dictated by the customer (which is a piece of knowledge belonging to the FR domain) were counted as '2' units of 'what' sub-division (because it describes the function of a part) in the FR domain. So in other words, this piece of information is 2 units of FR-What.

(b) Diagrams were regarded as a block of sentences. For the counting purposes, they were superimposed by a block of sentences of the same length as the diagram and counted as the number of lines in the block. For instance, a diagram of a part which consists of its dimensions and occupying 10 single spaced lines of space would be considered as 10 units of DP-what (dimensions represent design parameters and so this follows from our definitions in chapter 3).

However, this is an approximation in the case of information in diagrams due to several reasons. Firstly, the diagram could be presented in different scales of size that would affect the increase of count of the diagram by that scaling factor. Secondly, the amount of knowledge conveyed varies from diagram to diagram depending on the relative numbers of dimensioning, etc on it. The reason for this approximation was to simplify the process of counting. Perhaps we oversimplified it. However, it is also important to notice as an afterthought that the relative amount of information in diagrams as compared to the entire document is not significant. Hence the effect of diagrams to the document knowledge, in terms of units of knowledge and the counting procedure we have used is not significant.

(c) Tables were counted by the number of rows they contain. For instance, the following table is a System Design Specification requirement that the Electrical sub-division of Engine Intake System team at Ford would have to fulfill.

Alternator Components	**Steady State temperature (F)**
Inlet temperature	A
Regulator baseplate temperature	B
Front and rear bearing tempertuare	C
Stator core temperature	D

Table 4.2a. How to count tables

Note: The actual numbers have been masked by letters A, B, C and D for the company security reasons.

This table would be considered as 4 units of DP-what because they represent what the specific values of design parameters of the alternator components should be. Similarly, charts were also perceived in the same fashion.

For each page in the document, a page total of units of information were made for each category and the total number of lines in the page was counted. It was found in some cases, though they were of a negligibly small percentage that the total number of lines in a page does not equal the sum of lines of information in all categories for that page. This is because some types of information could be classified into more than one category. For instance consider the following task to be done during the testing of the throttle body. "The performance curve is made after the accelerator controls engineer provides data". This piece of information is counted both as 1 unit of 'OP-when' (sequence of activities: get data then generate performance curve) and 1 unit of 'OP-who' (responsibility of a person stated) even though it is just one unit of knowledge.

The various category totals are summed across all categories and the total for that document is computed. The percentage of total knowledge under each domain and sub-division in the document is also computed.

The same methodology is used for the three case studies, which we describe in the following two chapters.

4.3 Choosing the individual cases

The author studied three cases of product development process and the documentation they had respectively. The first case was with Ford Motor Company's throttle body development process. The second and the third were with CVC's (now Veeco) Metal Organic Chemical Vapor Deposition (MOCVD) chuck and Electrostatic chuck (ESC) development processes. It is important to note that the product development processes at these two companies are different in many aspects.

Firstly, the product development cycle times are different. The Ford throttle body development process is longer than the CVC's chuck development processes.

Secondly, the experience levels with developing the products at the two companies are different. Ford being the company that has been making throttle bodies since longer times than CVC's products that we studied, has more experience with the product development process of these respective products.

Thirdly, the work cultures at the companies are different because of the relative size and location of the product development teams. The CVC work culture is more people oriented because of the smaller team size and closer inter-personal communications. On the other hand, the Ford team is more spread out geographically because of the larger team unlike the CVC team, which has only two development sites.

Fourthly, for the products that we studied, CVC out sources a larger percentage of parts than Ford because they have to bring the products faster into the market even though they have less experience in developing their products relative to Ford. The author found that from the diagrams of the products studied and checking how many of them were made in-house.

Thus we have ensured during the case studies that there is adequate diversity in the product development processes to get a broader flavor as to how companies manage product development knowledge.

4.4 Chapter Summary

This chapter discussed the possible knowledge sources in a company to look for product design and development knowledge. It also described how this knowledge can be quantified and related to our PDKM portal. Then we noted the major differences in the product development processes among the case studies.

Part III
The cases

Chapter 5

Case I – Ford throttle body development process

"The case has, in some respects, been not entirely devoid of interest."

- Sherlock Holmes

5.1 Case Background:

This chapter looks into how Ford manages its knowledge about the throttle body product development process. The author looked into six different documents that were meant to help the designers during the various stages of the process. Five of them were design guides and one was the DSM of the process made by Qi Dong during her summer research at Ford during the summer of 1997. Out of the former five, two belonged to the different system groups of Engine intake and Air induction but working with the throttle body system group and closely influencing its design.

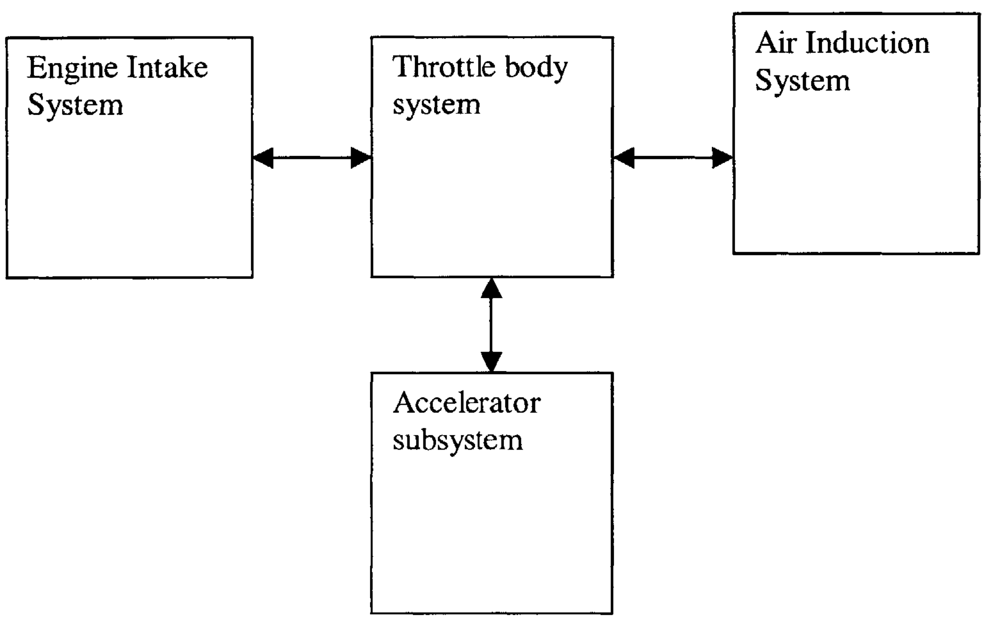


Figure 5.1a The three systems

5.2 Studying the individual documents

The six documents studied are discussed in this section. The first five are the various system design guides as shown in the following figure. Three of them were system guides (the three blocks in Figure 5.2a) and two subsystem guides related to throttle body system. The throttle linkage subsystem has no separate design guide because it contains just two parts of which one also belongs to the accelerator controls subsystem. The documentation for both parts and their interactions are contained in the above subsystem guide itself.

The sixth document examined is related to the DSM of the throttle body making process.

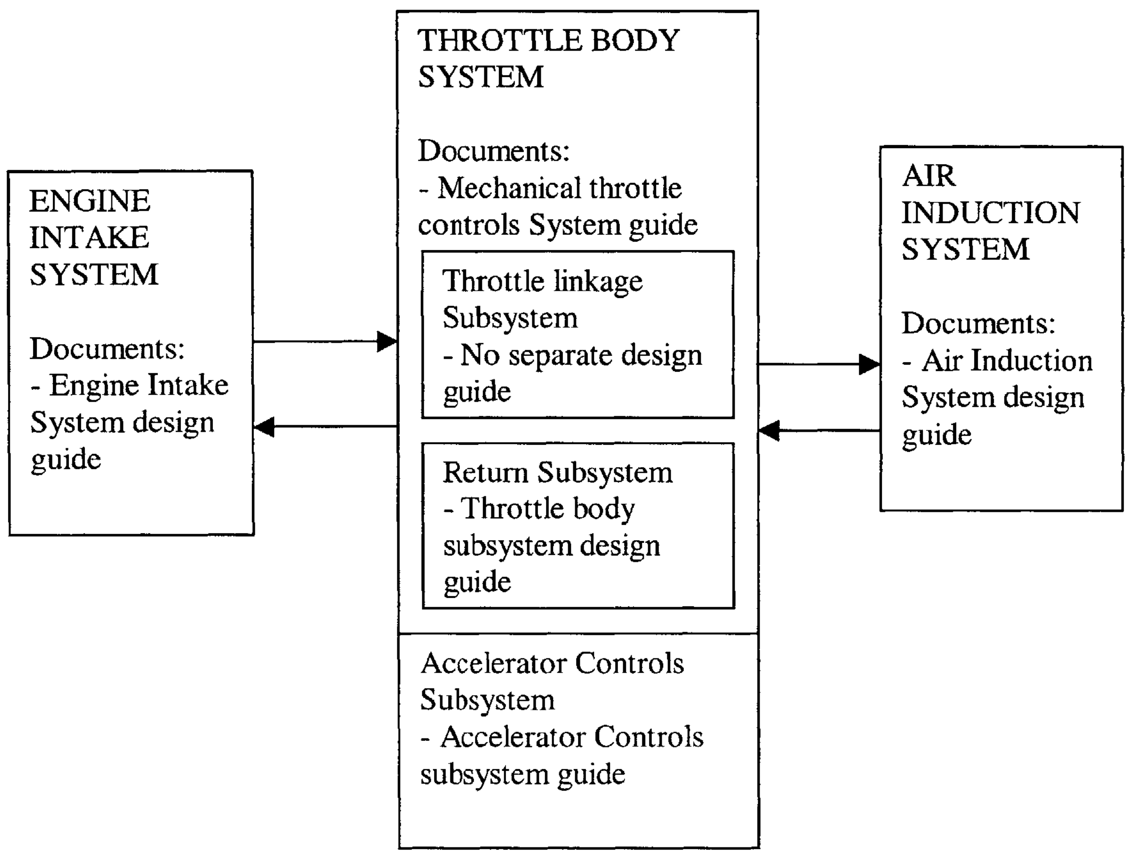


Figure 5.2a. Throttle body development process documents

The following Figure 5.2b shows the individual parts that make up each subsystem.

Accelerator Controls Subsystem:

1. Accelerator Pedal
2. Accelerator Cable
3. Acclerator bracket

Throttle Linkage Subsystem:

3. Acclerator bracket
4. Throttle accelerator linkage

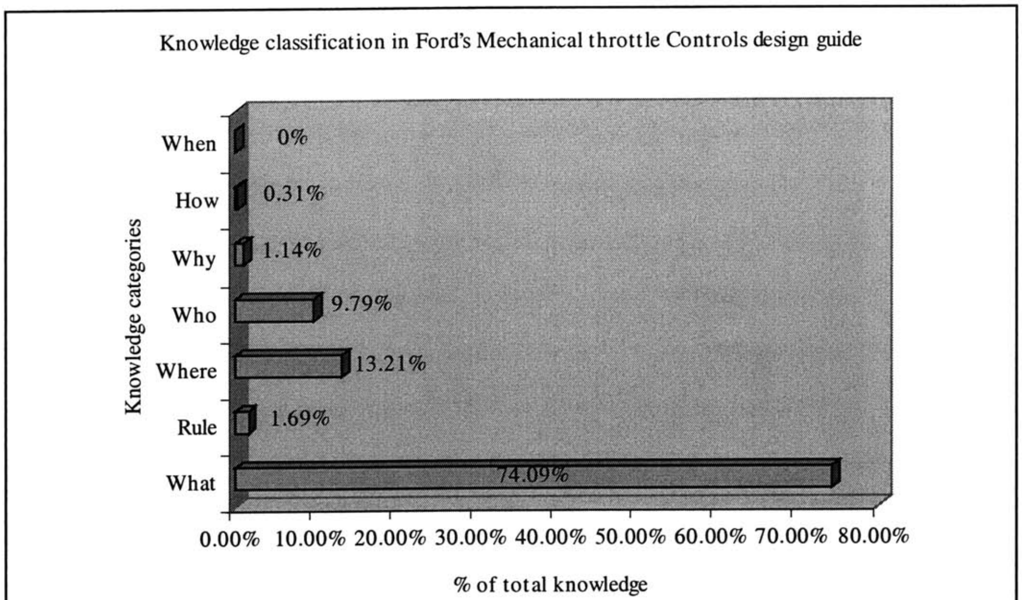
Return Subsystem:

3. Acclerator bracket
5. Accelerator return spring
6. Throttle return spring
7. Throttle return linkage
8. Acclerator splash shield.

Figure 5.2b Parts constituting the throttle body system

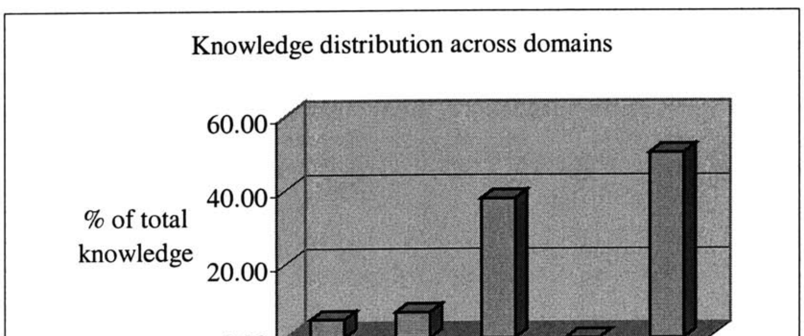
5.2.1 Mechanical Throttle Control System design guide

The function of the throttle control system is to provide the driver of the automobile with the means to control vehicle acceleration and speed. It also provides mounting points on the engine and throttle body for the speed control cable. This document had different features than the above. The results are as follows:



	What	Rule	Where	Who	Why	How	When
Series1	74.09%	1.69%	13.21%	9.79%	1.14%	0.31%	0%

Figure 5.2.1a Knowledge classification with the Mechanical Throttle Control Design guide



	CN	FR	DP	PV	OP
Series1	5.02	7.02	37.82	0.00	50.14

Figure 5.2.1b Knowledge distribution across domains

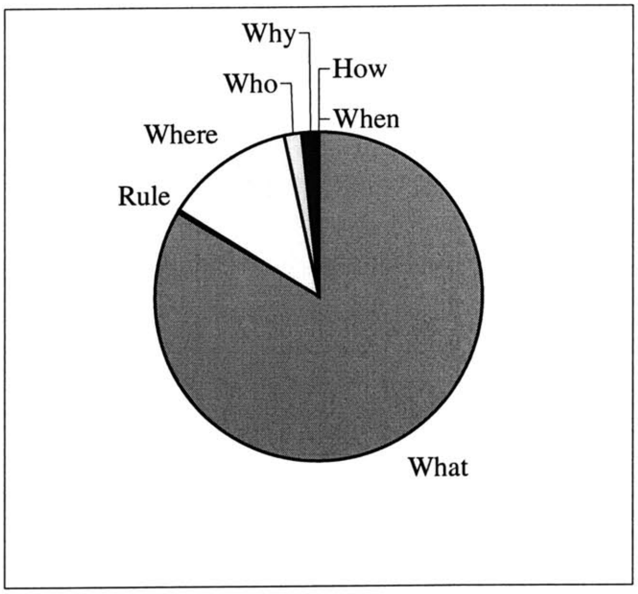


Figure 5.2.1c Knowledge distribution within the OP domain

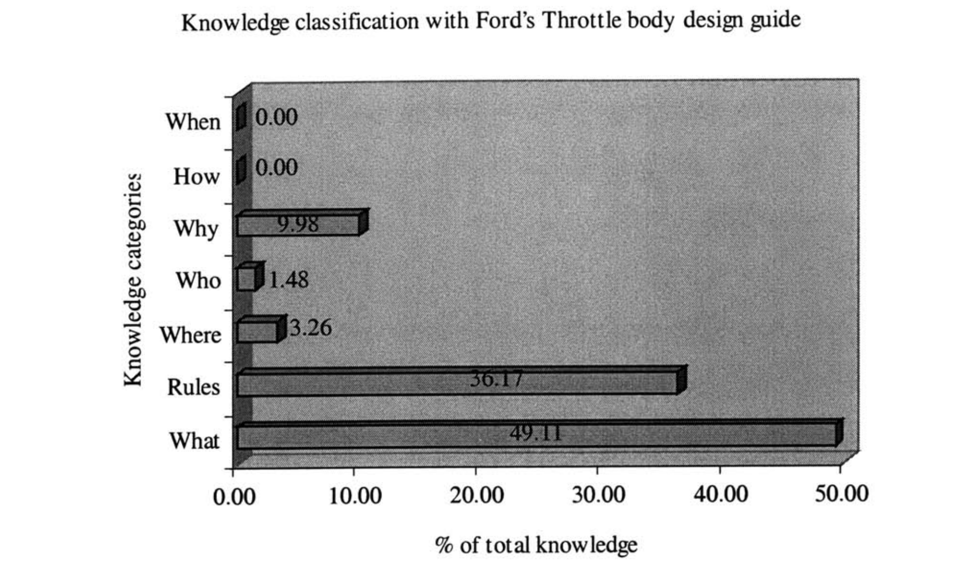
In this document, the OP and the DP domains held significant knowledge. This somewhat compensates the lack of the former in the earlier document. Note that the CN and PV domains still remain almost barren even after the two documents taken together. This is natural since the document was not designed to capture that knowledge.

The what sub-division continues its predominance over the other sub-divisions, only in this case the rules are much less relatively. One would expect that since the OP domain is pre-dominant that this would contain more rules and why2s given the experiences of failed test results and rework. However, this is not the case and it is a demerit, since it implies that the majority of the knowledge just addresses the routines in conducting the tests. However these are complemented better than the earlier document with more references since we see more 'where' and 'who' in this case. Note also that the how's and why's continue to elude the documents.

5.2.2 Throttle body system design guide

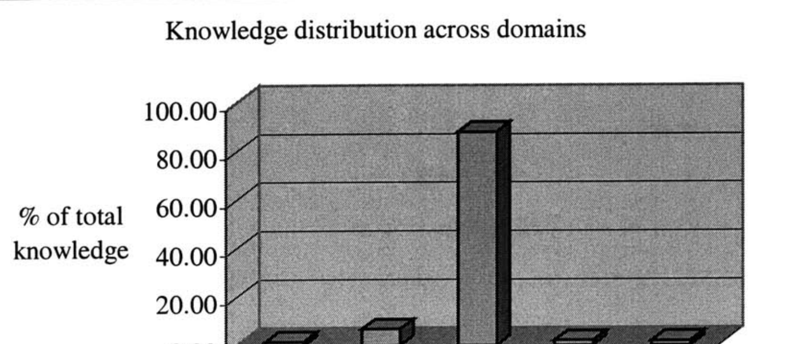
This document covers aspects related to the design of the various parts that make up the throttle body. It specifically looks at the component design, their design, manufacturing and system parameters for these parts.

The knowledge in this document scanned yielded out the following results.



	What	Rules	Where	Who	Why	How	When
Series1	49.11	36.17	3.26	1.48	9.98	0.00	0.00

Figure 5.2.2a Knowledge classification with Ford's Throttle body design guide



	CN	FR	DP	PV	OP
Series1	1.54	6.66	88.01	1.95	1.84

Domains

Figure 5.2.2b Knowledge distribution across domains

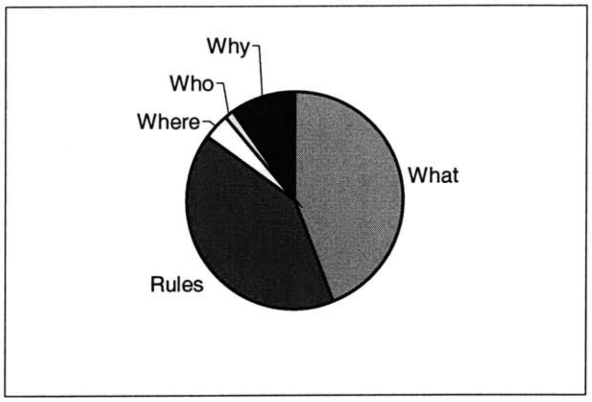


Figure 5.2.2c Knowledge distribution within the DP domain

The results can be explained as follows:

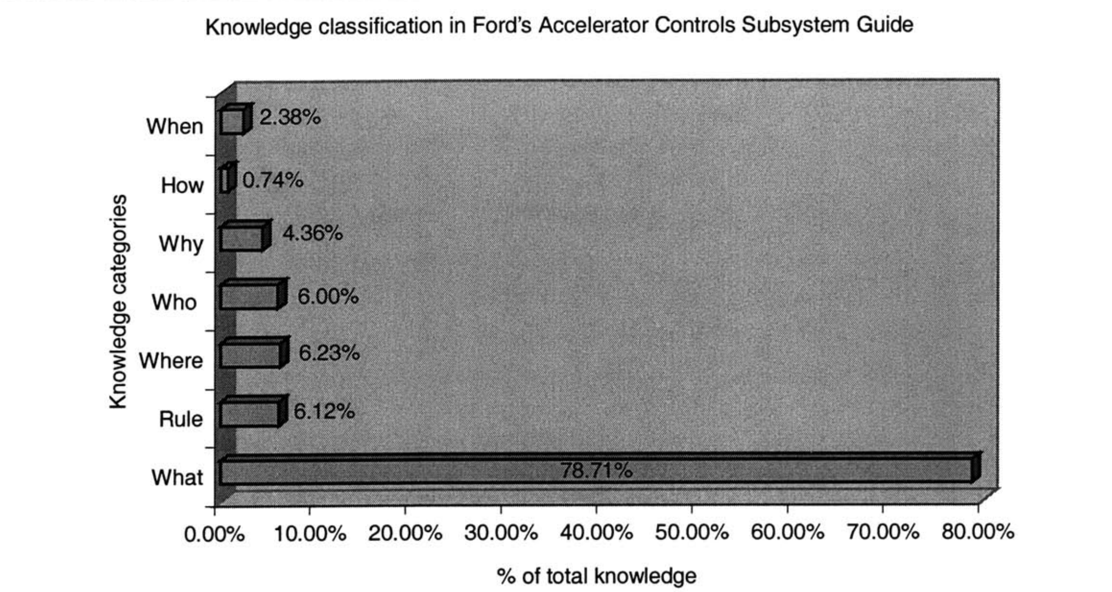
1. The knowledge is concentrated mostly in the DP domain as seen from Figure 5.2.2b. However there is very little flow or interconnection knowledge since how the designers came up with the parameters is not adequately described. This is evident since the information in the FR domain is little. Also, how these design parameters influence the process variable domain is further unclear since there is very little knowledge that belongs to that domain. Also, there are fewer references to the customer needs, which influenced the design parameters and lessons learnt from the testing procedures and their results to justify how well the design was found to be. Even though they don't specify these things explicitly in the form of rules or why2 categories, there is neither referencing to these domains in the form of 'who' and 'where' knowledge since they too form a negligible percentage of knowledge. This means people 'just know' these things which is

2. Among the sub-divisions, the knowledge is predominantly in the form of 'What' and 'Rules' as seen from Figure 5.2.2a. The justification for the rules is inadequate since there are fewer whys. Also the complete lacking of the how's further show the poor connection knowledge in the documents.

3. The knowledge within the dominant DP domain, as shown in figure 5.2.2c further highlights both the above statements.

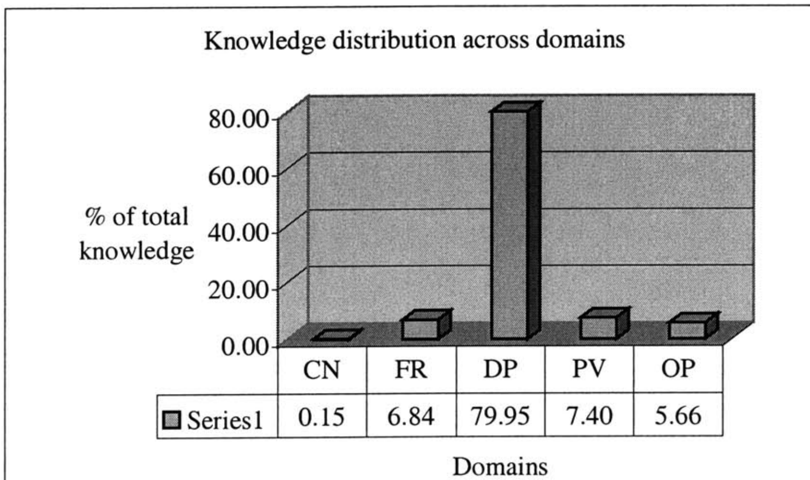
5.2.3 Accelerator controls sub-system design guide

This is a subsystem of the mechanical throttle controls and mainly consists of design elements involving the accelerator pedal assembly, accelerator cable assembly and accelerator engine bracket.



	What	Rule	Where	Who	Why	How	When
Series1	78.71%	6.12%	6.23%	6.00%	4.36%	0.74%	2.38%

Figure 5.2.3a Knowledge classification with the Accelerator controls subsystem design guide



	CN	FR	DP	PV	OP
Series1	0.15	6.84	79.95	7.40	5.66

Figure 5.2.3b Knowledge distribution across domains

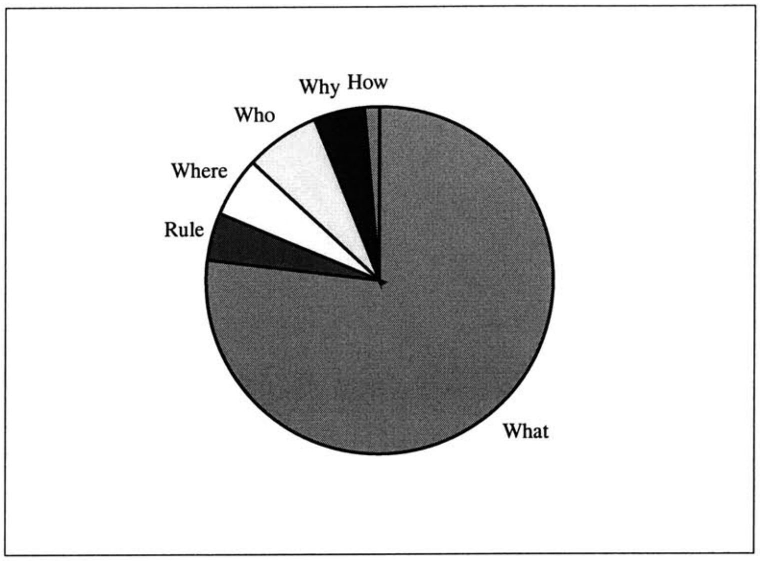


Figure 5.2.3c Knowledge distribution within the DP domain

Discussion:

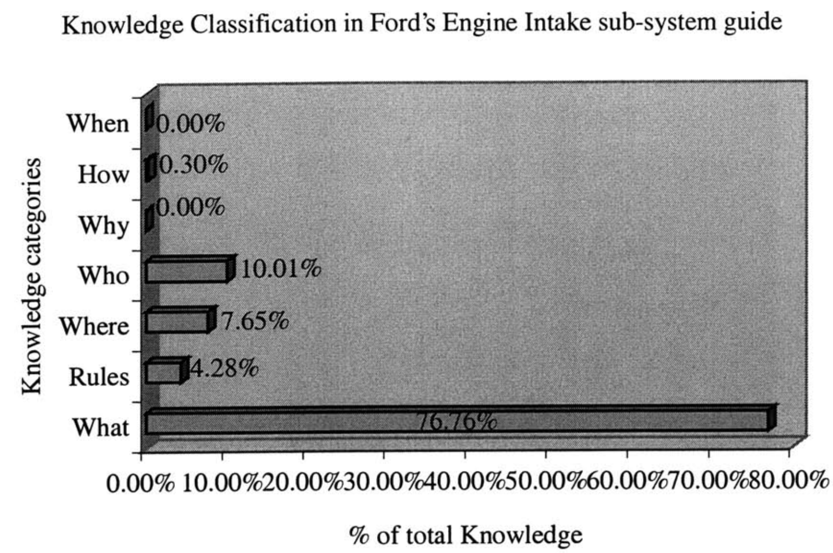
Here we again see the maximum knowledge in the DP domain. However, the PV domain, which was mostly barren earlier, has some information pertaining to the assembly guidelines and manufacture of the parts. However, all the other domains still lack knowledge.

We see more what's but here the rules again do not have enough justifications in the form of why's. Most of the whys in this case are why3's comparing several design choices and the best among those. The diagram also shows one rare case of when being documented in the form of the product development chart for this sub-system.

A higher number of who, why, how, where information supports the what and the rules in the DP domain as Figure 5.2.3c shows.

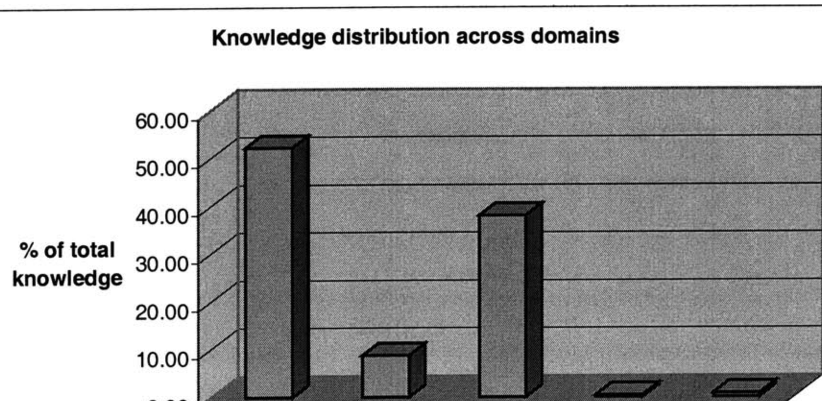
5.2.4 Engine Intake System guide

The results for this document are as follows.



	What	Rules	Where	Who	Why	How	When
Series1	76.76%	4.28%	7.65%	10.01%	0.00%	0.30%	0.00%

Figure 5.2.4a Knowledge classification with the Engine Intake System guide



	CN	FR	DP	PV	OP
Series1	52.15	8.70	37.96	0.41	0.78

Domains

Figure 5.2.4b Knowledge distribution across domains

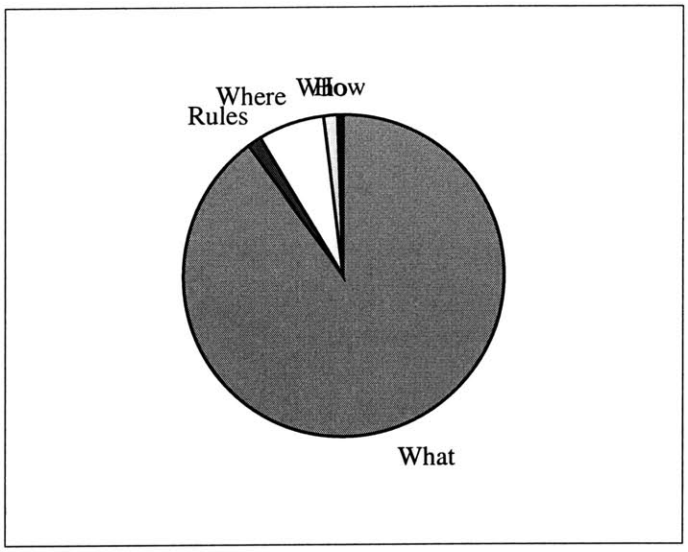


Figure 5.2.4c Knowledge distribution within the CN domain

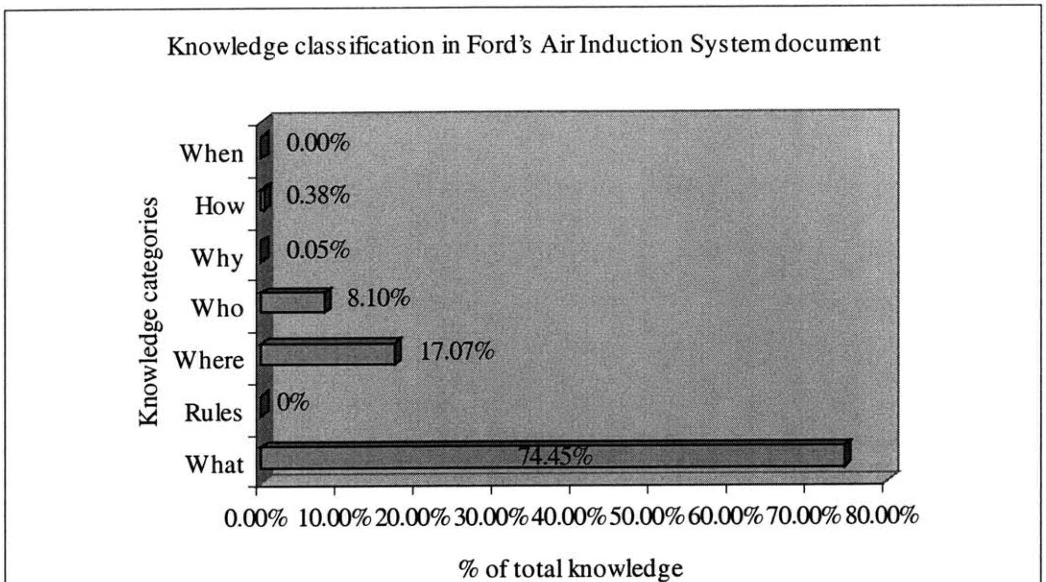
Discussion:

Though refreshingly the CN domain dominates in knowledge here, it does in a deceptive way because most of this knowledge in the document is in the form of glossary, which the Ford corporate defines for use during the design process. So though it appears like the CN domain is dominant, we could still say that the DP domain is more dominant because most of these definitions are of common knowledge to any designer/engineer – even those of who are novices.

Again, the 'what' knowledge rules the roost among the sub-divisions, with abundant 'who' and 'where' information to support it. Since the CN domain is full with the knowledge from glossary, figure 5.2.2c is of less consequence. The previous statement equally applies to this diagram as well.

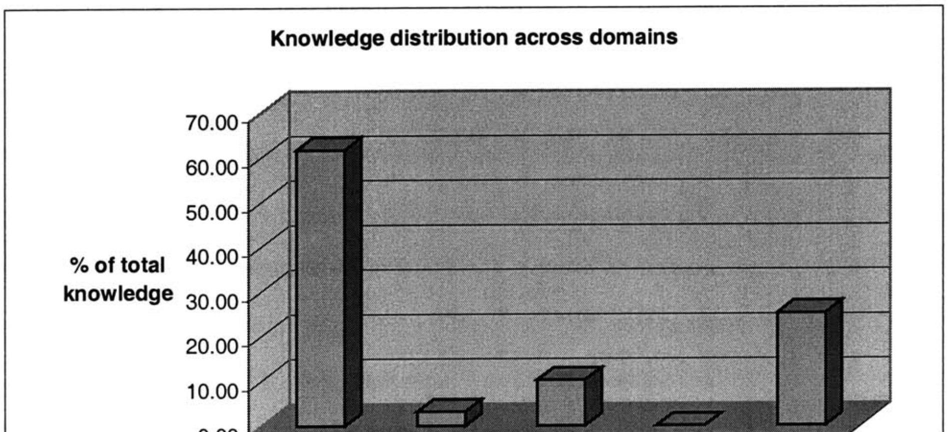
5.2.5 Air Induction system guide

The results for this document are as follows.



	What	Rules	Where	Who	Why	How	When
Series1	74.45%	0.00%	17.07%	8.10%	0.05%	0.38%	0.00%

Figure 5.2.4a Knowledge classification with the Engine Intake System guide



	CN	FR	DP	PV	OP
Series1	61.67	3.12	10.18	0.00	25.02

Domains

Figure 5.2.4b Knowledge distribution across domains

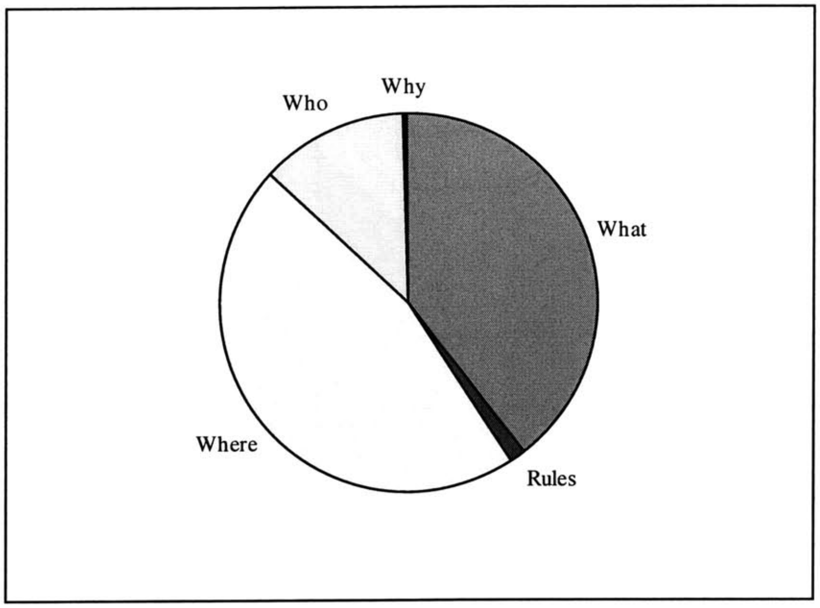


Figure 5.2.5c Knowledge distribution within the OP domain

Discussion:

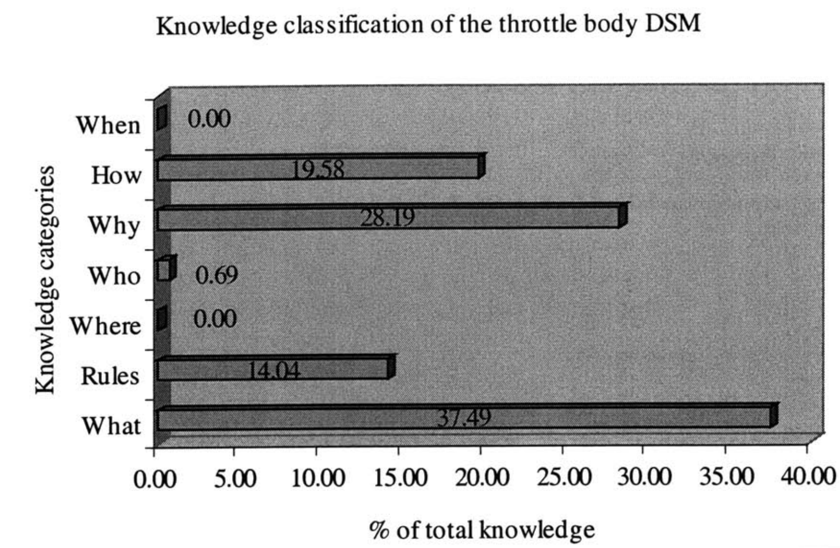
The CN and OP domains dominate in knowledge in these documents. The former again because of the glossary list it contains. Therefore the figure 5.2.5c is that of OP instead of the CN domain sub-divisions. It can noticed once again that the what sub-division is more popular than the more people-oriented knowledge categories such as rules, whys and hows.

5.2.6 Throttle body DSM

The author's research colleague, Qi Dong[16] during her summer research at Ford, prepared this document. DSM is a system analysis tool that provides a compact and clear representation of a complex system and a capture method for the interactions/interdependencies/interfaces between system elements (i.e. sub-systems and

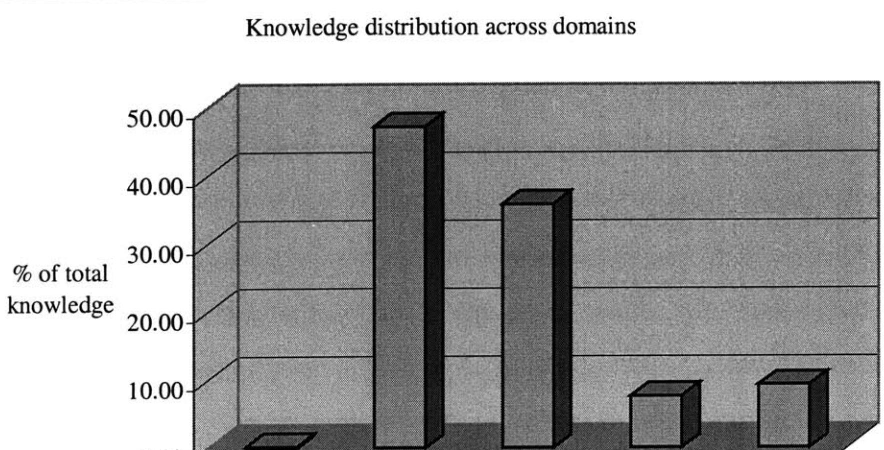
[16] Qi Dong, MIT thesis, February 1999.

modules). The following classification was made based on Qi's notes for constructing the DSM, which now also belongs to the company.



	What	Rules	Where	Who	Why	How	When
Series1	37.49	14.04	0.00	0.69	28.19	19.58	0.00

Figure 5.2.6a Knowledge classification with the throttle body DSM



	CN	FR	DP	PV	OP
Series1	0.20	47.20	35.81	7.55	9.24

Domains

Figure 5.2.6b Knowledge distribution across domains

The results indicate that for the first time we see improvement in the interconnection knowledge due to high occurrence of how (both how1 and how2 knowledge) and why (all three why1, why2 and why3 sub-divisions) as shown in Figure 5.2.6a. This is a significant result when compared to the knowledge found in the documents alone since they lack this knowledge. Hence DSM successfully captures the interconnection knowledge, much better than the documents themselves.

The FR and DP domain knowledge both dominate and it is interesting to note similar percentages for the two. The percentage of PV and OP domain knowledge is also in a different similar range. This implies that there is a good flow between domains, that one piece of knowledge in one domain is followed up in the subsequent domain, which we did not find with any of the other documents. The flow is reinforced by the large percentage of hows and whys.

During the construction of the DSM, some of the DSM links could be made by reading the documents themselves. However, a larger percentage of it was constructed by interviewing people involved with the project. The following figure depicts the ratio of the knowledge that was found in documents that went into the making of the DSM to that which needed interviews with people to figure out. The DSM notes of Qi Dong shows that this ratio for the throttle body process is 32% for the former and 68% for the latter. The reason for the higher percentage for the latter being the fact that people have interconnection knowledge much more than what the documents contain.

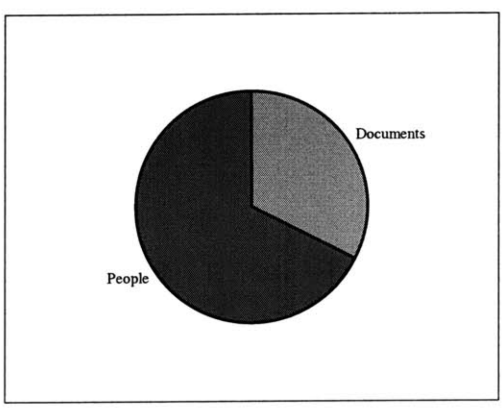


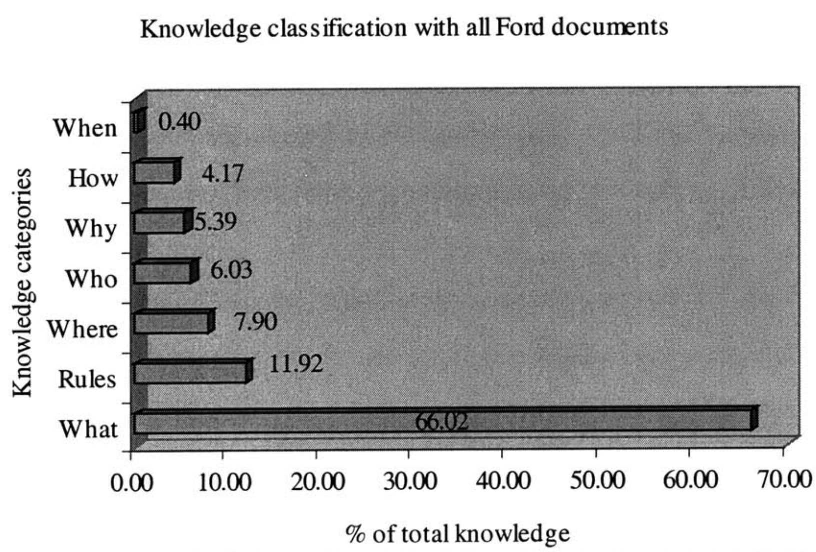
Figure 5.2.6c Percentage of knowledge in documents and in people's head – as the DSM shows.

5.3 Case-I results

This section discusses about the results shown when all the documents taken together as a throttle body product development knowledge documentation for the entire process. How the system guide documentation figures as against sub-system documentation is also discussed.

5.3.1 The documents taken collectively

This section presents the result of classification combining all the six documents taken together. The same diagrams showing how much of these percentages are from the contribution of the DSM to the knowledge building process for this case is discussed in Chapter 7.



	What	Rules	Where	Who	Why	How	When
Series1	66.02	11.92	7.90	6.03	5.39	4.17	0.40

Figure 5.3.1a Knowledge classification with the documents taken together

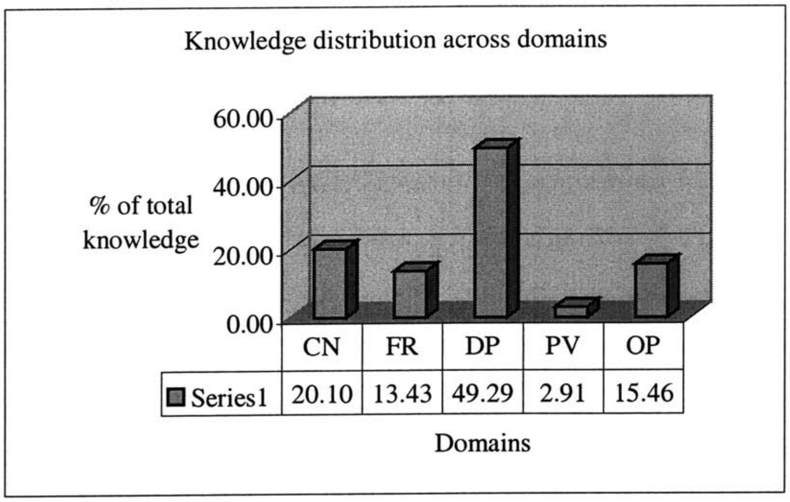


Figure 5.3.1b Knowledge distribution across domains

Though the CN domain seems to contain a lot of information, a lot of this is in the form of glossary which people would seldom refer to unless it is a critical one. The knowledge that is gained from interacting with the customers is seriously non-existent. This leads to people taking previous designs for granted since they start at a later design stage for improving the designs and end up either not meeting the customer's requirements or not being innovative enough about the product development process since they lack the CN domain knowledge. This factor thus could also contribute to longer product development times.

The low numbers for FR when compared to DP domain knowledge content shows that documenters focus on the design parameters more than the facts and reasoning that goes into establishing these parameters. Hence it could cause integration problems later in the process.

The PV domain lacks in almost all respects and is the least documented. This shows that people pay a lot of attention to the parts knowledge rather than the integration/assembly knowledge and hence face problems in the OP domain later, which could lead to rework and longer product development cycle times.

Though the OP domain contains relatively as much knowledge as in the FR domain, it is mostly testing procedures and not the results of the test that led to improvement in the design. Though this gets transferred to the other domains in the form of rules over a period of time, it does not clearly stated in the form of why2. So the valuable link between how the rule resulted because of a why2 is lost. This could lead to designers committing the similar mistakes again.

All the documents except the DSM represent the interconnectivity between the domains poorly. This is readily seen from the lower numbers for how1 and why1 and why2. There is not much reasoning for a given choice of design, which explains the scanty numbers for why3. The rules seem to just pop up out of nowhere and there are poor links in the entire process of documenting the product development process. The timing of the various tasks in the process is often neglected though the designers have specific milestones during the process – which is reflected in the sparse 'when' numbers. Though there appear to be many where and who knowledge they do not match the higher numbers of whats. However the fact that the knowledge is not in the documents does not necessarily prove that the knowledge itself doesn't exist. In fact, as found during the interviews while making the DSM, Qi Dong could construct a larger portion of the DSM. People just seem 'to know' these kinds of information through inter-personal communication without documenting it anywhere.

All this reflects a poor knowledge transfer methodology overall which leads to less than optimum innovation rate (not all people are innovating at the optimum rate because of the fact that the knowledge that they could have used to do a better job at that is not accessible to them because of poor knowledge management practices of the company) and product development cycle times (because of higher rework due to the same reason). The company also faces the danger of loosing the information when the experienced employee moves to another job function within the same company or elsewhere.

5.3.2 System guide documentation Vs Subsystem guide documentation

Though we would normally expect that the system guide would contain more of the interaction knowledge among the subsystems than the individual sub-systems themselves, the results do not show that in the form of relatively higher percentage of why, how and rules. They mainly specify which groups are collectively responsible for a certain parameter in the form of who. This again reflects that the real system knowledge lies within the people. However, it was found in this case that the subsystem guides did a better job at documenting the interconnection knowledge. This means that the people who were working of the individual parts had some idea about the system level implications of the parts they were working on and did a fairer job at documenting it.

5.4 Other means of knowledge transfer

The author did not have the chance to visit the Ford throttle body development facility. The knowledge based engineering software, which was built to facilitate knowledge collection and application automation serves as a browsable resource for the throttle body project information. However, email communication and the inter-personal communication through the meetings and discussions are the primary mode of knowledge transfer as it is shown by the Figure 5.2.6c.

5.5 Chapter summary

The chapter categorized the knowledge content of the documents related to the Ford throttle body development process and found it to be lacking on several fronts, especially higher level knowledge which is hard to get without experience. It showed that the DSM does a better job in this area as compared to the documents. The high dependence on people for such knowledge was also shown.

Chapter 6
Case II and III - CVC documentation

"A wealth of information creates a poverty of attention"
- Herbert Simon

This chapter discusses the documentation for two projects that the author looked into during the summer of 2000 at Veeco-CVC, Rochester, NY. The company makes silicon wafer handling stations/modules of which the wafer handling chuck forms a proprietary and primary component. It is a relatively small design and production facility, which out sources many components of the products it makes but assembles them together along with the some key company made components in those assemblies. It provides leading edge metal organic chemical vapor deposition (MOCVD), Ion beam deposition (IBD), Ion bean etching (IBE), physical vapor deposition (PVD) systems for data storage, MEMS, optical and telecommunications networks and other applications.

6.1 Case II - MOCVD Chuck project

The MOCVD module is equipped with a substrate chuck capable of handling 150 mm and 200 mm silicon wafers and equipped with computer controlled temperature control subsystem capable of heating upto 400° C. Copper and other metal depositions on the wafers are carried out in the module with the chuck clamping the wafer during the process. The chuck assembly has a stepper motor style linear actuator and controller for variation and control of velocity and acceleration of the chuck table top. The system is also equipped with the proprietary enhanced backside gas conduction subsystem for timely heating of the substrate.

The documents containing information related to the chuck were scanned for their content and how well they fill up the knowledge categories of the PDKM portal. The three documents associated with the process were MOCVC Phase III folder, MOCVD module specifications and Wafer chuck specifications guides.

6.1.1 MOCVD module specifications guide

Observations:

Since the specifications form a major part of this document, the FR-Whats in Figure 6.1.1a are in huge numbers. This is the most mandatory part of documentation at CVC along with the drawings of designs. The percentages are only relative, whether all the specifications regarding functional requirements are captured or not is not known.

Though the documentation for the project is relatively small, the references are in large numbers as indicated by a large percentage of 'where' info. This is usually not a good practice if all the documentation is primarily on paper since it makes searching through the various folders difficult. However it is good in case of intranets.

The main drawback in this case, is the higher level knowledge is represented poorly. We can conclude that from the inconspicuousness of Rules, Why and How knowledge categories in Figure 6.1.1b. However there is a good transition from the FR to the DP domain unlike what we have seen previously. This is seen by the adequate cross-referencing between the two domains in the form of 'where' knowledge as shown in Figure 6.1.1a. This is a good way of documentation that the Design Matrix supports well but in a much better fashion, since with every FR there is a corresponding DP. The higher domain knowledge of OP reflects the test routine whats.

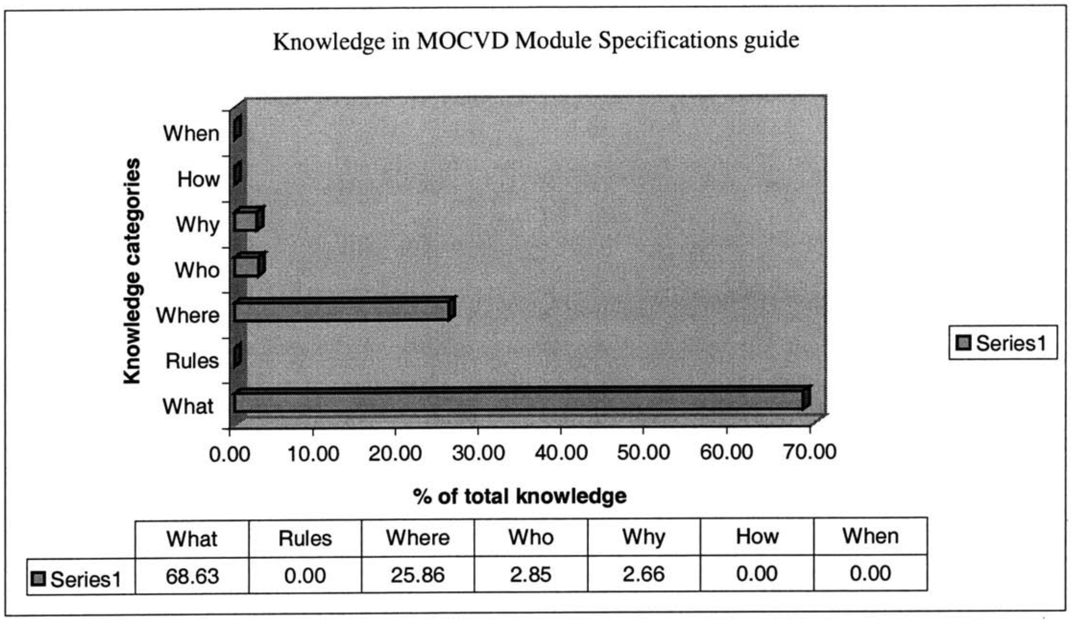


Figure 6.1.1a Knowledge classification with MOCVD module specifications guide

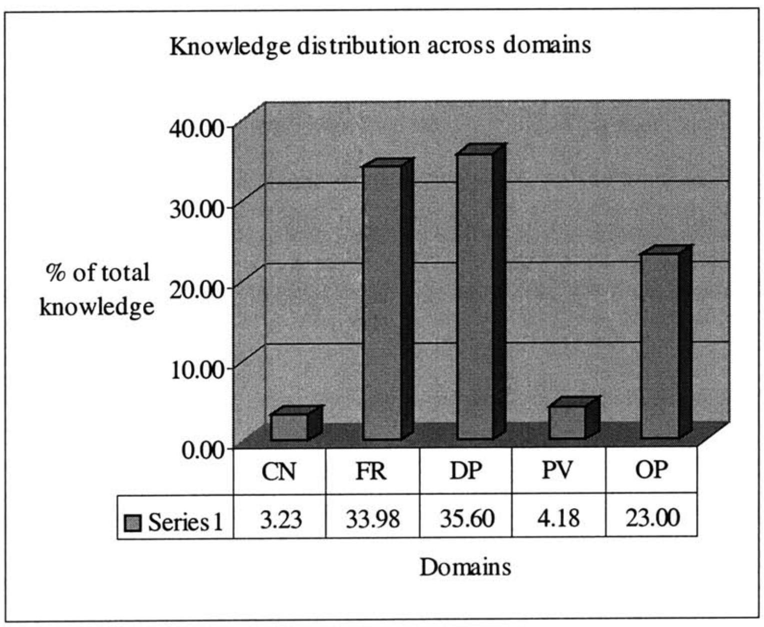
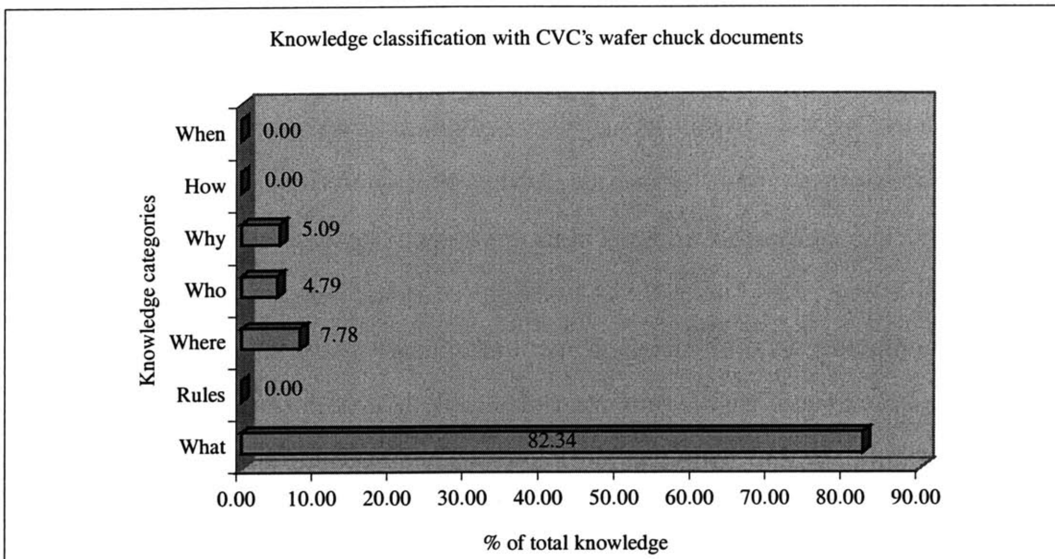


Figure 6.1.1b Knowledge distribution across domains

6.1.2 Wafer chuck document

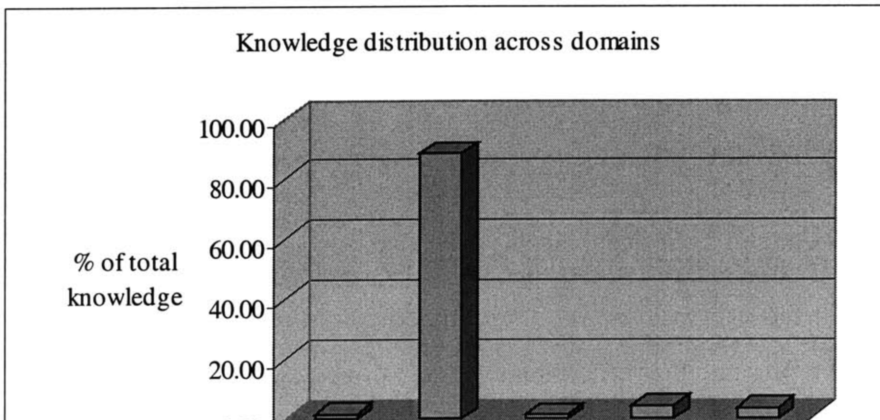
This is similar to the MOCVD module specifications document in terms of knowledge percentages in the various domains– predominantly what and where. The same conclusions as above hold here too.

However, the whats in FR are not justified well since there is not much interaction across domains as shown by the negligible amount of both CN or DP domain knowledge, the domains connecting to the FR domain.



	What	Rules	Where	Who	Why	How	When
Series1	82.34	0.00	7.78	4.79	5.09	0.00	0.00

Figure 6.1.2a Knowledge classification with the wafer chuck guide



	CN	FR	DP	PV	OP
Series 1	1.85	88.31	1.54	4.62	3.69

Domains

Figure 6.1.2b Knowledge distribution across domains

6.1.3 MOCVC Phase III folder

This badly maintained folder mainly contains drawings along with a few testing procedures and design review meeting minutes of an earlier generation product of the company, which is similar to the MOCVD project. It was primarily meant to serve as a reference for the MOCVD project itself. The design review meeting minutes contain insufficient documentation about important issues that were discussed regarding the problems faced during the design implementation stages. These are the areas which give rise to very important system level knowledge – rules, whys and hows but are insufficiently documented. The chances of encountering those problems don't reduce in similar future projects unless it is documented or people from the same team work on the new project. The author found from the interviews of designers at an earlier stage during the summer research that such a case would not occur during the later MOCVD project because most of the designers for both the projects were the same. However, the author also noted towards the end of the testing stage of the MOCVD project that as the company merged with another company, Veeco, many of the designers left the company and it lost all this valuable information. This clearly highlights the danger of improper or insufficient documentation.

6.2 Case III - ESC cold chuck project

The company started to project after discovering the need for a different kind of chuck in the market, which was a need not well met by the competitors of the company according to the design team for the project. So the company started developing the Electro Static Chuck (ESC) during the summer of 1999 after a customer survey was made to determine the exact needs of the market. A detailed survey of the existing products of the competitors was also made for setting higher-level design standards to make this product better than the existing ones.

6.2.1 ESC Cold Chuck folder

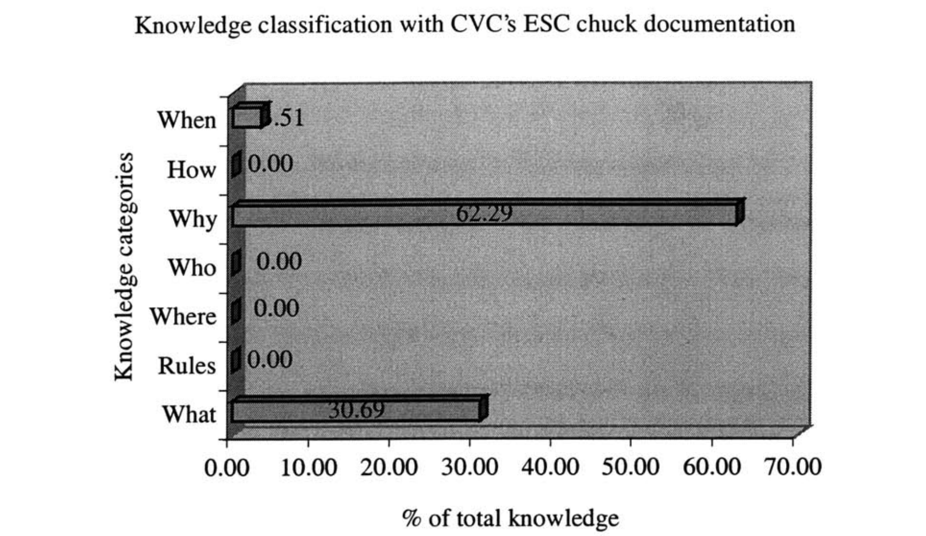
Observations:

This documentation is better in several aspects compared to the MOCVD chuck project, though again it is insufficient in some other aspects.

Its good to see that this document contains analysis of the various vendor designs against the product CVC wants to build along with that for the latter design. FR-Why3 represents this and forms the largest % of knowledge group as is evident from Figures 6.2.1a and Figure 6.2.1b.

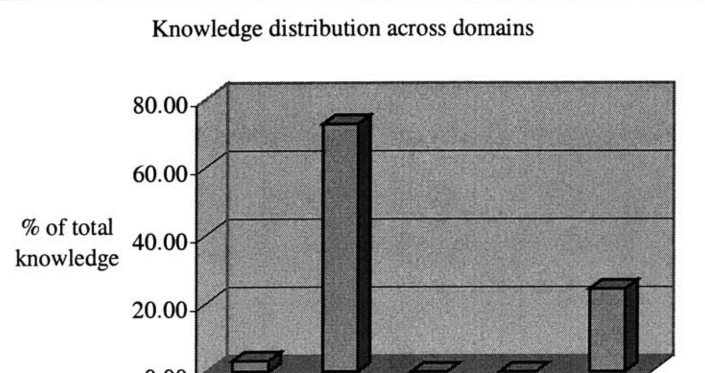
Companies don't usually document the CN-What and OP-What well, as proved by the documents of Ford. CVC does better in this area but again the percentages are relative to that particular document as shown by Figures 6.2.1b and Figure 6.2.1c, so the actual completeness of the documentation is hard to judge.

The major drawback with the documentation for this product development process is that rules were yet to be documented till the end of last year when the product delivery was due. The problems during testing and integration phase need to be documented to help avoid facing similar problems in the subsequent projects of similar nature. The documentation in the form of drawings alone is insufficient. Understanding the drawbacks and the potential problems is key to avoiding re-work in design, which takes up a lot of time. This is more relevant to CVC since build and see if it works – redesign seems to be the culture at CVC. Though this maybe due to the short product development times, it could be made efficient by proper documentation of trouble-shooting, etc.



	What	Rules	Where	Who	Why	How	When
Series1	30.69	0.00	0.00	0.00	62.29	0.00	3.51

Figure 6.2.1a Knowledge classification with the ESC chuck guide



	CN	FR	DP	PV	OP
Series1	3.14	72.67	0.00	0.00	24.20

Domains

Figure 6.2.1b Knowledge distribution across domains

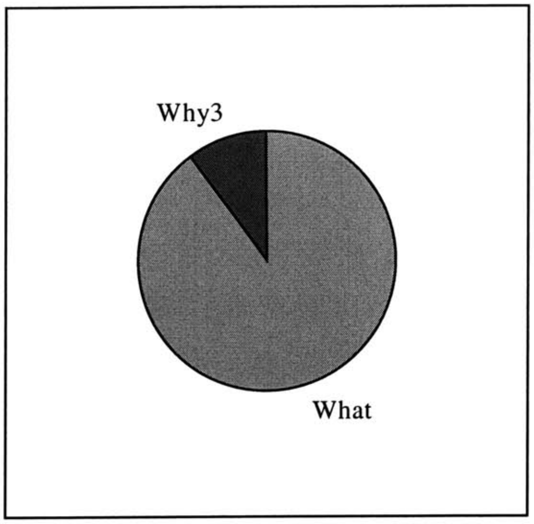


Figure 6.2.1c Knowledge distribution within the FR domain

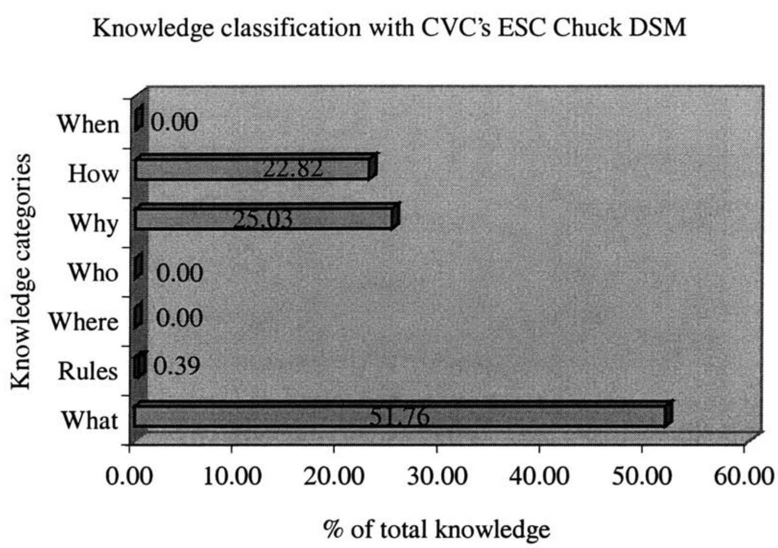
6.2.2 EBSG ESC Cold Chuck DSM

This document was made by the author's research colleague, Qi Dong[17] during her summer research at CVC along with the author during the summer of 2000.

Observations:

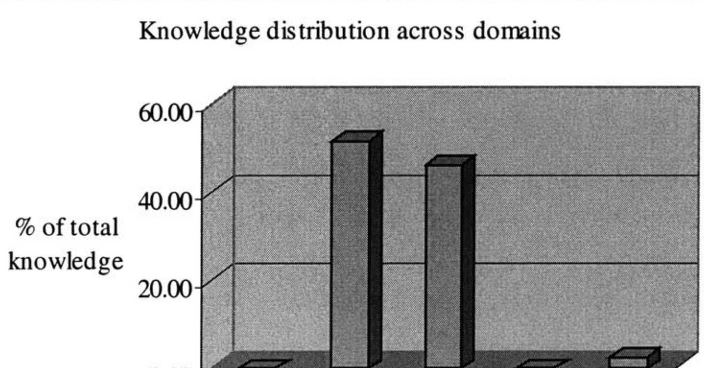
1. The comparison between the ESC document graph and ESC DSM shows how DSM can add value to the company knowledge base. The under-represented categories in the documents – FR-What, Why1 or How1 (flow down knowledge) is complimented with the DSM since these form the majority of knowledge in the DSM.
2. Besides this a novice starting work on a project can learn quickly about the major bottlenecks in the entire process by studying or building a DSM, since they carry high-level system knowledge in an easy to understand form. This compliments the mandatory documentation of the FR knowledge well.

[17]Dong, Q. and D. E. Whitney. "Designing a Requirement Driven Product Development Process". ASME 2001 International Design Engineering Technical Conference, 13th International Conference on Design Theory and Methodology. DETC2001/DTM2007.



	What	Rules	Where	Who	Why	How	When
Series1	51.76	0.39	0.00	0.00	25.03	22.82	0.00

Figure 6.2.2a Knowledge classification with the ESC DSM



	CN	FR	DP	PV	OP
Series1	0.00	51.50	46.02	0.00	2.48

Domains

Figure 6.2.2b Knowledge distribution across domains

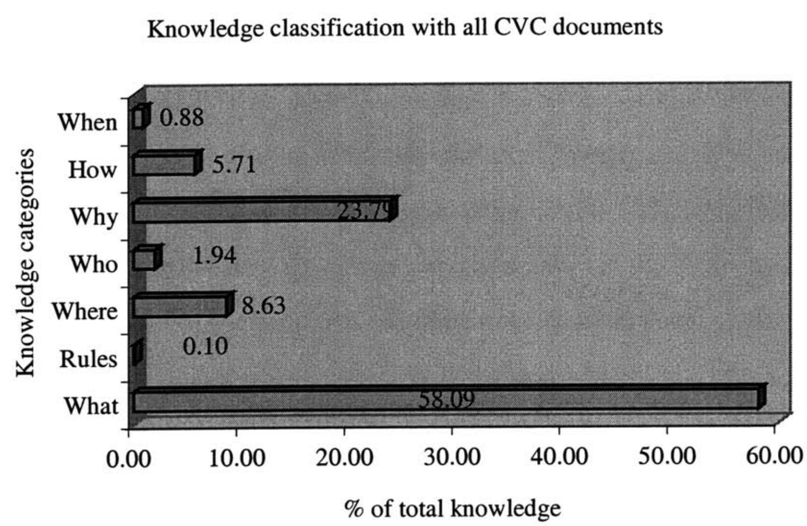
6.3 Combined results of CVC documents from the two projects

The combined results of both the above projects give us the following tables and Figures. We note that the FR domain knowledge is best documented and DP domain comes next. Since there was little OP knowledge in the first MOCVD project, we could expect that the next generation ESC project would contain more OP domain knowledge. In fact, this is actually the case. The designers would have realized that documenting this knowledge would indeed be important once they get into troubles with the testing stage. The PV domain knowledge is almost negligible. One of the main reasons for this being the fact that a lot of parts that go into the chuck project are outsourced. However, even in that case the documentation relating to the problems with their assembly and the information about the suppliers is missing. The assembly is at best as good as its parts. Dr. Whitney talks about this knowledge that Honda has, that has helped it gain a core competence in dealing with its suppliers that other car companies envy about. There is little knowledge that is documented in the other domains. According to the author's observation at the company, the CN domain knowledge that was primarily with one person left the company after the merger. So the knowledge about going to the customer and assessing their demands and converting them to the FR domain knowledge was lost to the company. Similarly, the design team involved with the DP domain also weakened since more people left the company. The ESC project was left hanging in air during the OP stage with the remaining product development left in the hands of the inexperienced engineers with no OP domain knowledge even in the document form to fall back upon during need. Earlier the who category knowledge played an important role in communication of knowledge which was now almost non-applicable due the employees leaving the company.

Among the sub-categories we find that only 'what' and 'why' knowledge figure consistently across all documents. The why knowledge mainly being 'why3' type 'why' giving alternative designs. There are almost no 'rules' and 'hows' in the documents, which is a bad sign since they contain higher-level interconnection and experience knowledge. This is particularly important for a small company like CVC where the employees leaving the company and fresh employees joining is more frequent.

	% of knowledge in the domains						
Documents	**What**	**Rules**	**Where**	**Who**	**Why**	**How**	**When**
Wafer chuck	82.34	0	7.78	4.79	5.09	0	0
MOCVD chuck	67.58	0	26.72	2.95	2.75	0	0
ESC chuck	30.69	0	0	0	62.29	0	3.51
ESC DSM	51.76	0.39	0	0	25.03	22.82	0

Table 6.3a Knowledge classification with all CVC documents



	What	Rules	Where	Who	Why	How	When
Series1	58.09	0.10	8.63	1.94	23.79	5.71	0.88

Figure 6.3a Knowledge classification with all CVC documents

	% of knowledge in the domains				
Documents	**CN**	**FR**	**DP**	**PV**	**OP**
Wafer chuck	1.85	88.31	1.54	4.62	3.69
MOCVD chuck	3.33	67.32	29.35	0	0
ESC Chuck	3.14	72.67	0	0	24.2
ESC DSM	0	51.5	46.02	0	2.48

Table 6.3b Knowledge distribution across domains

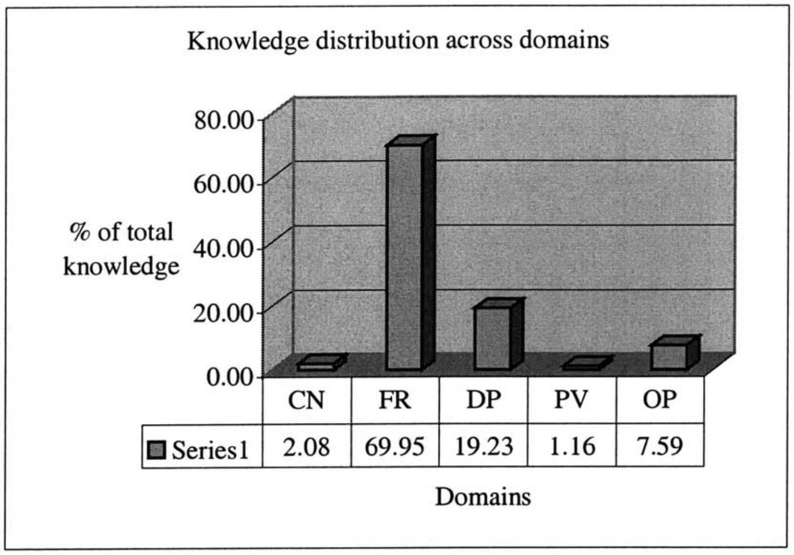


Figure 6.3b Knowledge distribution across domains

6.4 Chapter Summary

We studied four documents from two projects of successive generation at CVC. They show poor knowledge documentation and high dependence on people for knowledge transfer. Even this high dependence on people was not justified during the recent company merger and the loss of designers to the company.

Part IV
Conclusions and future work

Chapter 7
Comparison results across all the cases

"It is often wonderful how putting down on paper a clear statement of a case helps one to see, not perhaps the way out, but the way in."
- A. C. Benson

In this chapter, we summarize the findings about the three cases and compare them against one another and discuss the benefits of using DSM and software tools on the product development knowledge management process.

7.1 Comparing Ford Vs CVC documentation

We now compare the documentation at Ford and CVC in general in the context of the PDKM portal.

1. The documentation for the project is relatively small at CVC, as shown by the number of units of knowledge in the three cases.

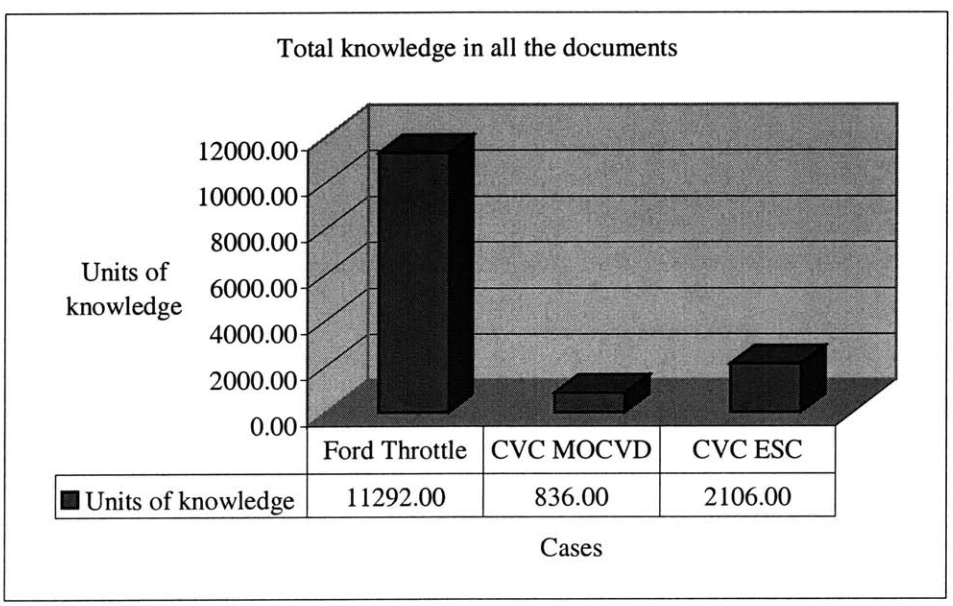


Figure 7.1 Total amount of knowledge in the cases

2. Maintaining a good glossary serves to quickly understand the meaning of technical terms and what they mean in the context of this company. Though the relative percentages are good in case of CVC, it could be improved. Building a common glossary for individual projects could be done henceforth and then those relating to all the other projects can be added to one common company glossary. The implementation of an intranet within the company for such things could serve the company well. Ford does this and hence a good portion of the CN-what is comprised of these glossary-whats.

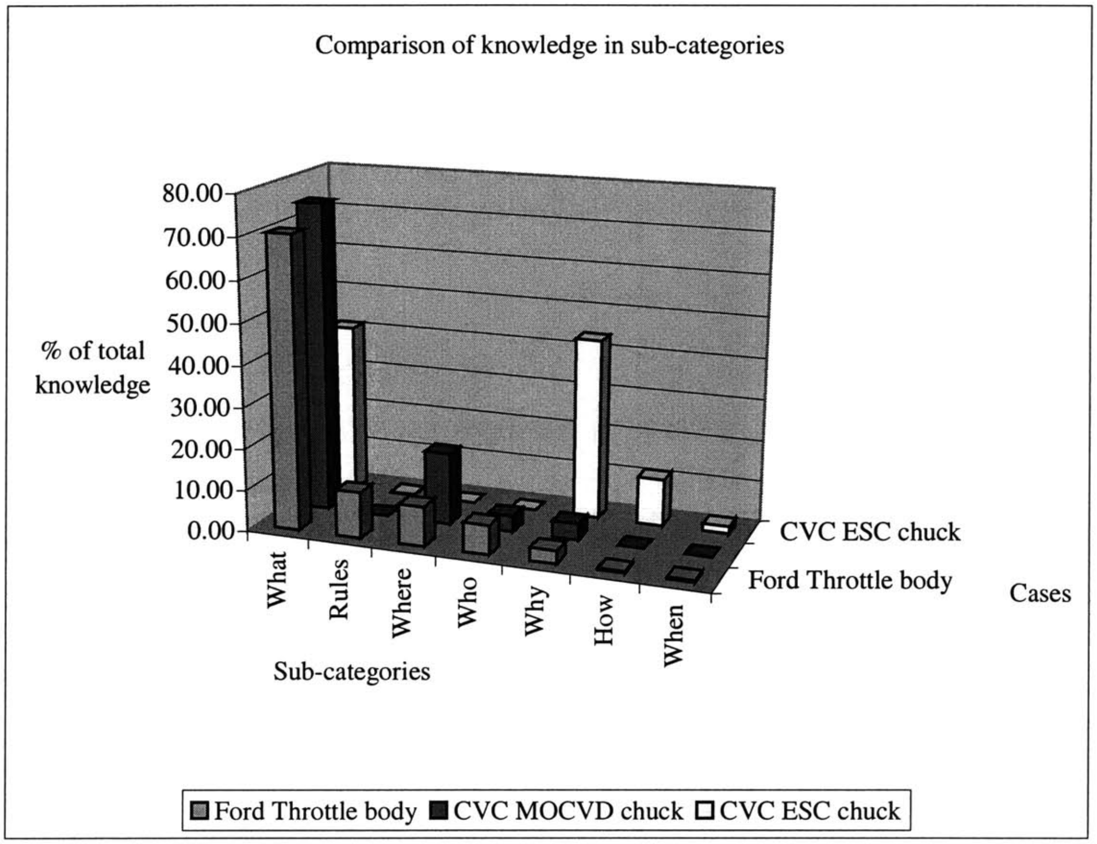


Figure 7.1b Comparison of knowledge sub-categories for the three cases

3. The references are in large numbers in case of CVC relative to the total amount of knowledge, as indicated by a large percentage of 'where' info in case II. However, who info is much less since the team size is small and the team members are generally aware who to contact for a particular segment of the process or task. As the team size gets bigger in bigger projects a larger number of 'who' and 'where' would be necessary.

4. The sub-categories of rules, how, when and why (except for case III) are under represented in all three cases. This requires understanding and hence is more of a people-oriented knowledge. Companies need to do a better job in documenting these higher-level knowledge categories in order to promote interconnection knowledge and knowledge from experience.

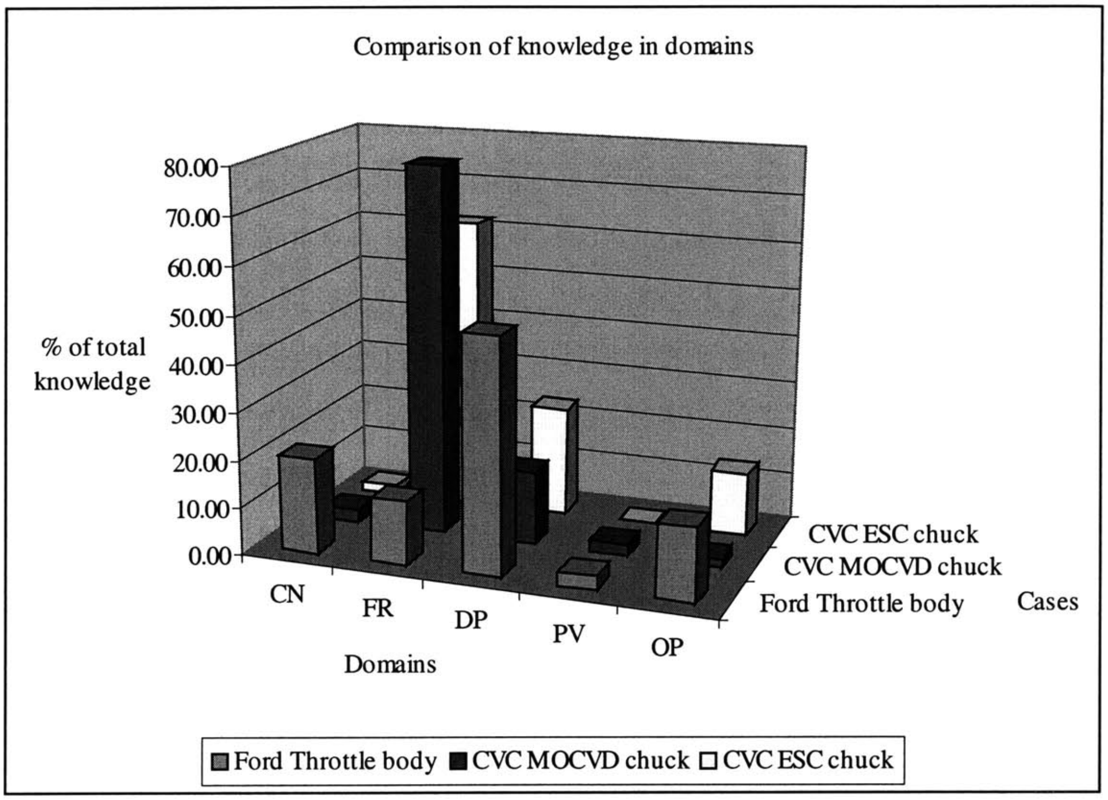


Figure 7.1c Comparison of knowledge in the domains for the three cases

5. Among the domain knowledge, FR and DP domains are the best represented. Ford has a good CN domain knowledge in the form of enterprise knowledge, which CVC lacks. PV domain is under-represented in all three cases. This shows that assembly knowledge and manufacturing knowledge are not well accounted for. This has the effect of creating system level problems towards the end of the product development process. The OP knowledge is primarily in the form of whats and so the learnings and rectifications of a bad design and rework are also not well documented. Thus learning which occurs during

these stages is more ignored than the other domains. This often leads to re-invention of the wheel and rework and prolongs the product development cycle.

7.2 Contribution of DSM to the knowledge building process

The following figures show how the DSM has added to the existing knowledge base for the project. The DSM along with the side-notes that the DSM maker, Qi Dong used during the making of the DSM shows that the DSM is a very valuable tool as a knowledge-capturing device as well. To add to its usefulness, it is worthwhile to note that the added knowledge is more in the form of higher-level knowledge categories such as rules, why and how which was lacking in the documents as the earlier Figure 7.1b shows. In case of Ford throttle body, it adds the much elusive PV domain knowledge too. Its also commendable because a few pages of DSM is more than equivalent to many pages of documentary knowledge for the cases. Thus DSM could be used as a complement to the documents as a stand-alone knowledge source.

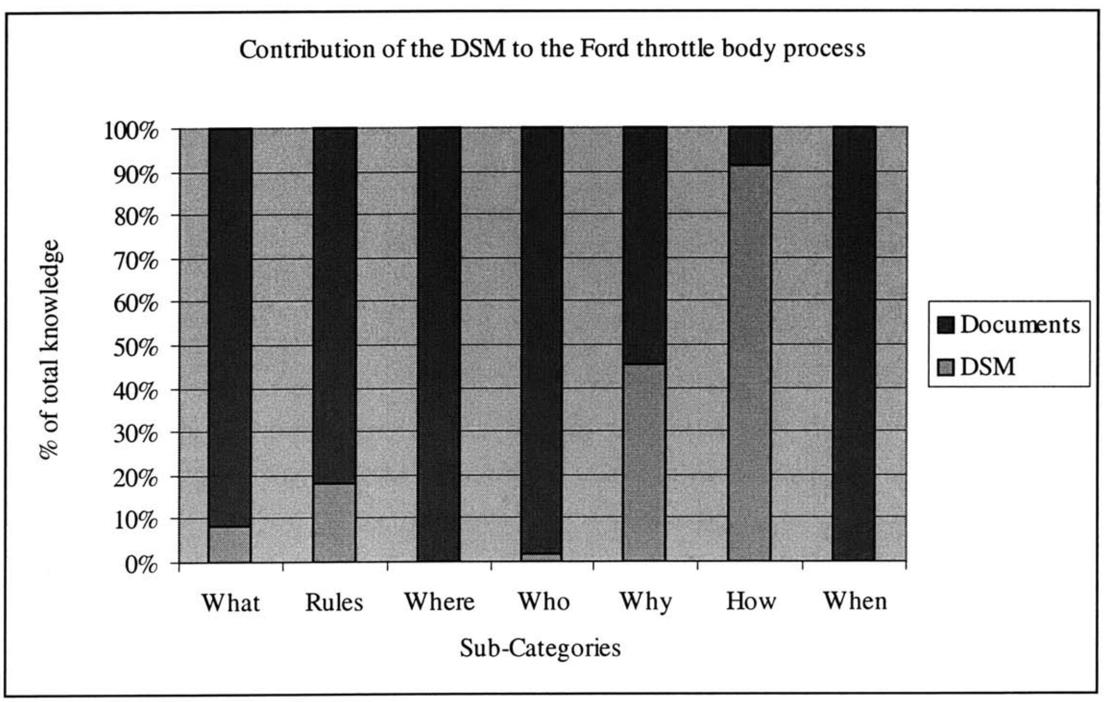


Figure 7.2a Contribution of the DSM to the Ford throttle body process knowledge subcategories

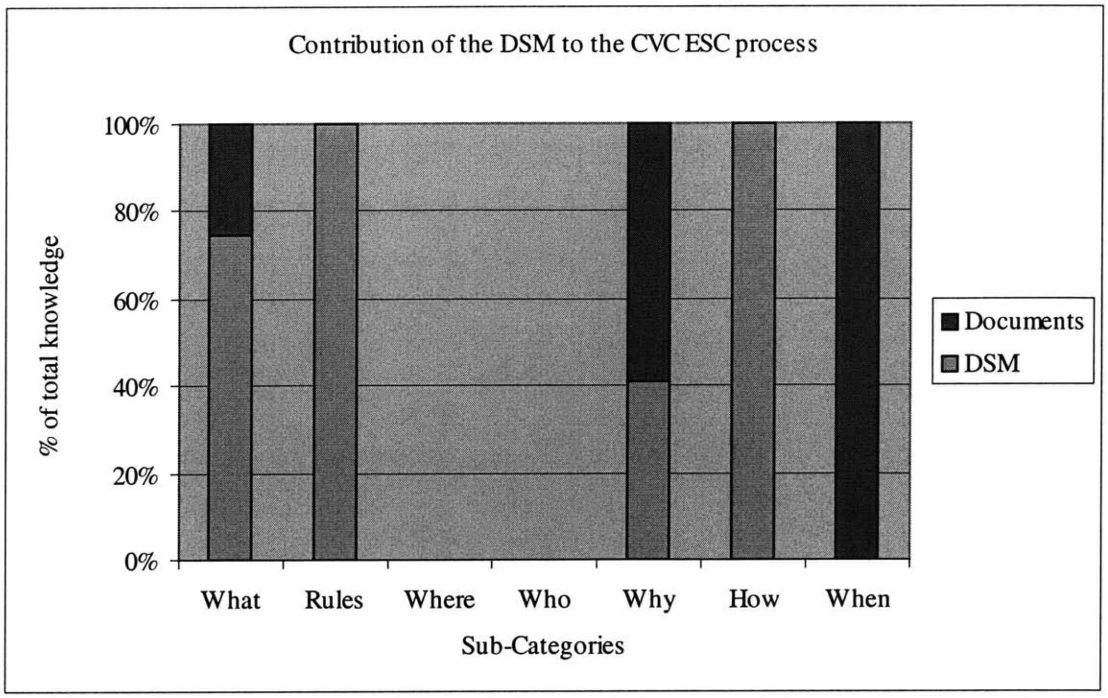


Figure 7.2b Contribution of the DSM to the ESC process knowledge subcategories

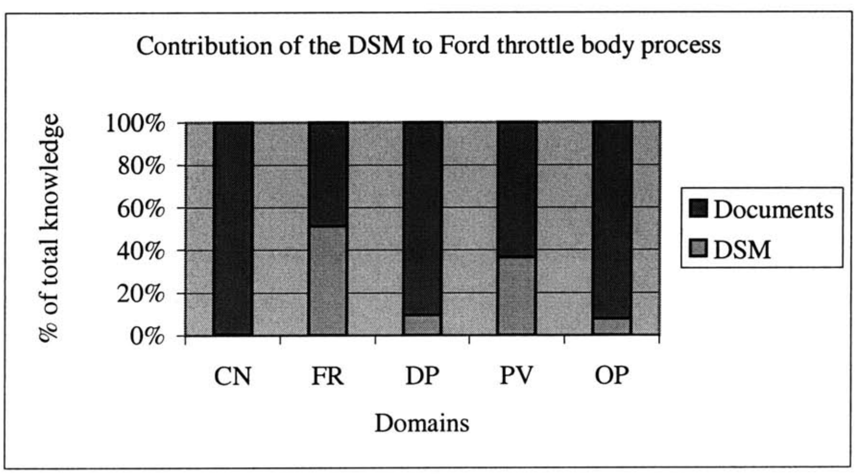


Figure 7.2c Contribution of the DSM to the Ford throttle body process domain knowledge

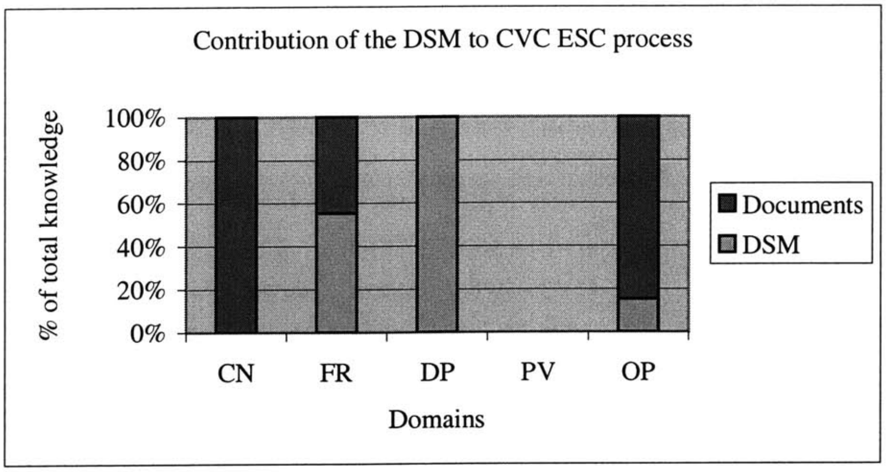


Figure 7.2d Contribution of the DSM to the ESC process domain knowledge

7.3 Reliance on people as a means of knowledge transfer

Comparison of the Ford DSM and the CVC DSM notes shows that almost one third (33%) of the DSM can constructed with documents alone at Ford as against about 5% DSM that can be made with CVC documentation. This represents that system level knowledge is in a very poorly represented form at CVC.

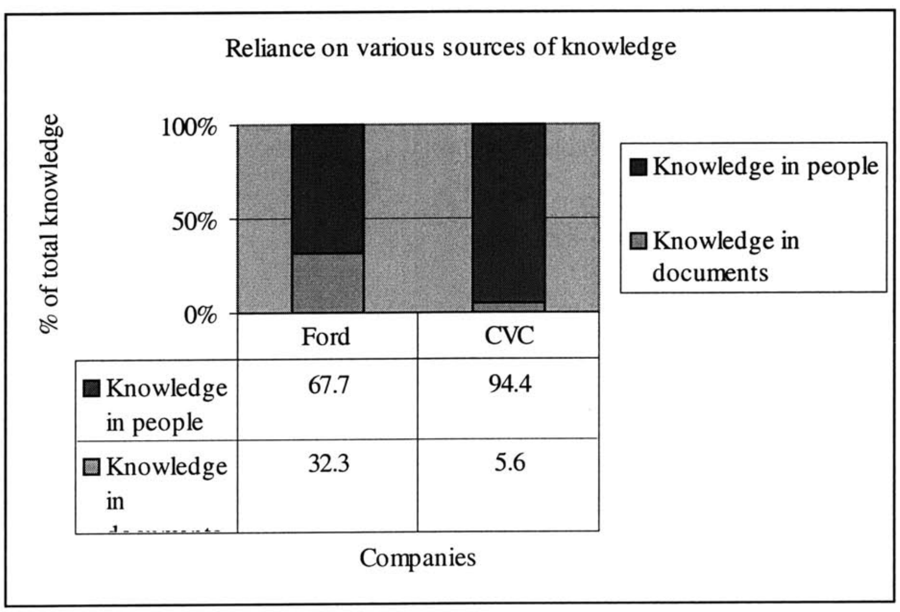


Figure 7.3a Reliance on the two primary knowledge sources

The above numbers also indicates a very high reliance on people-to-people communication at CVC as compared to Ford. Though this has its merits, system level documentation is necessary as a company grows and employees move onto senior positions and take newer/more responsibilities. The junior engineer is then likely to repeat the same mistakes as his/her predecessor with little supervision. Good documentation lessens that problem.

Also, the author found that a lot of design review meetings where discussions of rework and design revisions and rework were discussed, very few documents on meeting minutes and lessons learnt during them were found in the project folders. This is another bad case of not documenting valuable knowledge. CVC had an additional problem due to the merger when the key people who worked on the ESC chuck project left to other companies. This is a fine example of the price the company pays for such high reliance on people alone.

7.4 Reliance on software tools

We saw in chapter 2 how the usage of software tools could have a major impact on the product development knowledge management process. The author found that CVC doesn't use any kind of special software aids to help in documentation and knowledge browsing. Ford does that using an intranet, which is a knowledge repository of all kinds of design information.

Though the documentation for the CVC project is relatively small, the references are in large numbers as indicated by a large percentage of 'where' info. This is usually not a good practice if all the documentation is primarily on paper since it makes searching through the various folders difficult. However this could be remedied through building intranets.

7.5 Chapter Summary

In this chapter, we compared the results of the three cases in the context of our PDKM portal. We highlighted the demerits of each and also explained the valuable role of DSM as a stand-alone knowledge source for product development process. We also highlighted that too much reliance on people alone could be dangerous and discussed the impact of using software tools for the knowledge management process.

Chapter 8
Future Research

"Some day, on the corporate balance sheet, there will be an entry which reads, 'Information'; for in most cases, the information is more valuable than the hardware which processes it."
- Grace Murray Hopper

8.1 Future research directions

Future studies could proceed in two directions simultaneously: Improving the PDKM portal itself; Study the portal under a variety of product development settings and test it for wider applicability.

We have shown that the PDKM portal could be a useful tool in capturing the inter-connection knowledge and much better than some of the other ways of knowledge retention in companies. More studies could be done to more firmly establish this.

Studies could be conducted to show that the interconnection knowledge is the key to improving product development process. Using the counting methodology and the portal as discussed in Chapters 3 and 4, now we would have metrics to quantify and say if one product development process knowledge documentation is better than the other. However, what this study would not prove is if the process itself is better. The reason for this being the fact that not documenting does not mean people do not know the knowledge itself and hence do not use it in the process.

Case studies could be conducted to prove that innovation comes from interconnection knowledge. This would require us to have a clear definition of innovation in the light of the portal. Since we have already proved that the PDKM portal is good for documenting interconnection knowledge, this would mean that the it is good for innovation as well.

Case studies could be conducted to study the impact of documentation and no documentation for successive generations of a particular product development. The first case would be to study a product where documentation almost doesn't exist. The second case would be to study the next product development of the same product, which now has documentation. Then the amount of time spent reinventing the wheel could be determined through interviews and establish that documentation cut the product development times and increased the knowledge base.

The same exercise could be repeated with the documentation now being in the form of the PDKM portal instead of the usual way the company documents product development knowledge. This would establish the usefulness of the portal over the other forms of documentation. Then there would be data to support how the PDKM portal is actually better than the usual methods of documentation and also how it affects the product development times.

Both these two exercises could be done in parallel.

During the case studies using the PDKM portal, establishing the portal and knowledge sub-categories in the form of object oriented software databases that are suitably cross-linked to show the several links in the portal that we discussed could be done. Appropriate security permissions could be set for updating the relevant segments of the portal by one or more persons depending on the 'who' information. The inter-connections could give us a snapshot of the entire process, be it whether the sequence of tasks and responsibility of people other than the interconnection knowledge in the form of why and how. The portal would also help the company in bringing the knowledge content in several sources under one link-rich and consistent framework. A sample example of building the database for the case of the wallet design was shown in section 2.3 of the thesis.

The cases could be repeated to evaluate in what kind of product development settings the PDKM portal is most useful. Whether it is best suited to develop where the product development cycle times are short or long; where the company work cultures are different – one promoting people-to-people communication more than the other; where the company's product development is done locally or through geographically distant teams working together.

All these exercises would increase the scope for further refinement to the portal to make it into a better tool that is widely applicable across a variety of product development processes and easy to use at companies.

An entirely new avenue of research could focus on the value of knowledge. Knowledge can be primary or derived. The latter is the knowledge that can be inferred from the former through experience. Taking the example in section 2.2.2, we can say that if 'Data' is the primary knowledge, 'Information' is the derived knowledge. Similarly, if Information is primary knowledge, 'Knowledge' is the derived knowledge. Thus we have an increasing level of 'wisdom' in the successive stages. Similarly with the eight stages of knowledge in section 2.2.10, we see increase in the value of knowledge from 'complete ignorance' in stage one to 'complete knowledge' in stage eight. In the case of our PDKM portal wallet example in section 3.3, if 'the wallet length and breadth ratio should be 3:2' (a FR-what) is a primary knowledge, 'Wallet lengths and breadth are to be of two types. Type 1 will have a size of 3 inch by 2 inch; Type 2 will have a size of 3.15 inch by 2.1 inch." (a DP-what) would be derived knowledge. Research could proceed to assign value to individual pieces of information. Note that the derived knowledge carries more value than the primary knowledge in most cases. Thus a 'knowledge value index' for the entire knowledge base for a project could be developed. By assigning these indices for several projects in this fashion, comparing how good their knowledge bases becomes quantifiable based on the knowledge value index.

8.2 Chapter summary

Future studies could proceed in two directions simultaneously: Improving the PDKM portal itself; Study the knowledge content in more cases with the portal under a variety of product development settings and test it for wider applicability.

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